THE PROPERTIES AND GENESIS OF FOUR MIDDLE ALTITUDE DYSTRANDEPTS FROM MAUNA KEA, HAWAII

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By

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INTRODUCTION

Hawaii is one of the volcanic areas of the world. Volcanic ash is widespread throughout, and many soils contain ash as part of their parent material. The soils derived from volcanic ash contain predominant amorphous mineral colloids that have high chemical reactivity. The properties of these soils are very different from the soils formed from other parent materials.

Hawaii is also a unique place where, in a relatively restricted area, soils derived from similar parent materials and of nearly identical geological age vary in degree of weathering and development. Different soils are found within short distances due to large variations in climate.

The sequence of soils under study was obtained from the northern slopes of Mauna Kea. In this sequence of soils the only important variable factor is climate. All soils are derived from volcanic ash; thus the parent material is fairly constant. All soils are in similar slopes and aspects without any water table influence.

The Hydrol Humic Latosols on which sugar is grown have received much study, but the soils in the higher elevations have not been studied extensively. The proposed study will provide information about the soils at higher elevations.

The main objectives of this research are:

(i) To characterize the soils

(ii) To study the effect of rainfall and temperature on soil formation

(iii) To examine and modify the classification of andepts, if necessary

REVIEW OF LITERATURE

Nature of Volcanic Ash

Volcanic ash is the fragmental ejecta from magma, produced by being crushed, flung high into the air by eruption, suddenly cooled, and fallen to the ground. The erupted materials are collectively called pyroclastics and only the particles of the size of sand and dust grains are called ash. The coarser materials are called Lapilli or Cinders according to their size. Usually the coarser material is found closer to the original volcano and finer materials are distributed at a considerable distance by air currents depending on the mode and intensity of eruption.

In Hawaii mantles of volcanic ash are found overlying many of the lava flows. Swindale and Sherman (1964) discussed the nature of this volcanic ash in Hawaii by dividing them into three types depending upon their composition and modes of occurrence.

1. Andesitic ash:

The rocks on eastern Oahu, most of Molokai and Maui and on the northern and northeastern parts of Hawaii are covered with deposits of andesitic ash of varying thickness. Due to the high amount of silica and soda, the andesitic differentiation product of the original magma became so viscous that instead of flowing like lava, it is flung out as ash by violent explosion. Houng (1964) examined the sand fractions of a number of soils derived from this ash and found oligoclase and andesine feldspar, olivine,

enstatite, a little augite and the accessory minerals apatite and magnetite. He also found glass shards having brownish to greenish-brown colors and refractive indices higher than Canada balsam.

2. Phreatic Basaltic Ash:

This ash is found mainly in the southeastern part of the island of Hawaii. According to Frazer (1960) this is formed by phreatic explosions from Kilauea Volcano. These ash deposits are collectively called Pahala ash. According to Stearns and Macdonald (1946), this ash consists of pale brown or brownish green pumiceous glass fragments and in some places the glass is altered into yellowish brown to orange mineral called palagonite. This ash also contains olivine and plagioclase feldspar ranging from bytownite to labradorite. No information is available about the presence or nature of accessory minerals.

3. Basic and Ultrabasic Ash:

These deposits are mainly basic and ultrabasic volcanic glass which has been extensively altered at least on the surface to red, yellow and orange products known collectively as palagonite. Olivines, pyroxenes, feldspars and felspathoid minerals have been identified in the cinder deposits.

Properties of Soils Derived from Volcanic Ash

Morphological Properties

All soils derived from volcanic ash do not have the same

morphological features. It depends on the grade of weathering of the parent material, soil formation, topography, vegetation, climate, etc. In Japan, most workers think that the soils which they call "Kuroboku" represent the most conspicuous features of volcanic ash soils (Takehara, 1964), and the other volcanic ash soils of different morphological properties are derived from "Kuroboku". This soil has a thick pitch black A horizon with high humus content. The soil is friable when dry and becomes very sticky when it is wet (Ohmasa, 1964). The B horizon is massive and usually has a brown color.

In Hawaii, Cline (1955) found that most of these soils have a dark colored A1 horizon and relatively high organic matter, that grade to a lighter colored B horizon. According to Swindale and Sherman (1964) these soils have either AC or A(B)C profile with friable or very friable A horizons. Flach (1964) (in one of his papers) said that the most outstanding characteristic of the Ando-like soils is the tendency of the soil to appear moist when undisturbed and wet when crushed, i.e. "smeariness". In the field these soils tend to have an intermediate apparent texture but when analyzed in the lab it is found to be much finer. These soils sometimes show partly cemented layers due to the movement of silica, iron or manganese (Birrel, 1964).

In the U.S.D.A. soil classification (1955), the group andepts which include most of the soils derived from volcanic ash,

are considered to have an ochric, mollic or umbric epipedon and if the epipedon is ochric the soils have a cambic horizon. Many of the Andepts have received repeated ash falls and buried A1 horizons are found.

Mineralogical Properties

The sand fraction usually contains volcanic glasses and some of the other rock forming minerals such as feldspars, pyroxenes, hornblende, magnetite and very little or no mica (Swindale, 1964; Birrel, 1964). In most of these soils, the secondary minerals are dominated by allophane or other amorphous minerals. The term allophane was defined in different ways by different authors (Swindale, 1964).

The presence of allophane was observed as early as 1914 by Seki in Japanese soils. Allophane of geological origin was found and described by Ross and Kerr (1934). Birrel and Fieldes (1952) analyzed clay fractions of New Zealand volcanic ash soils and concluded that the principal clay mineral in the clays is allophane. In Hawaii, Kelly and Page (1943) found considerable amounts of amorphous material in certain soils. Tamura et al. (1953, 1955) on studying the mineral content of Low Humic, Hydrol Humic, Humic Ferruginous Latosols found appreciable amounts of allophane in some of these soils.

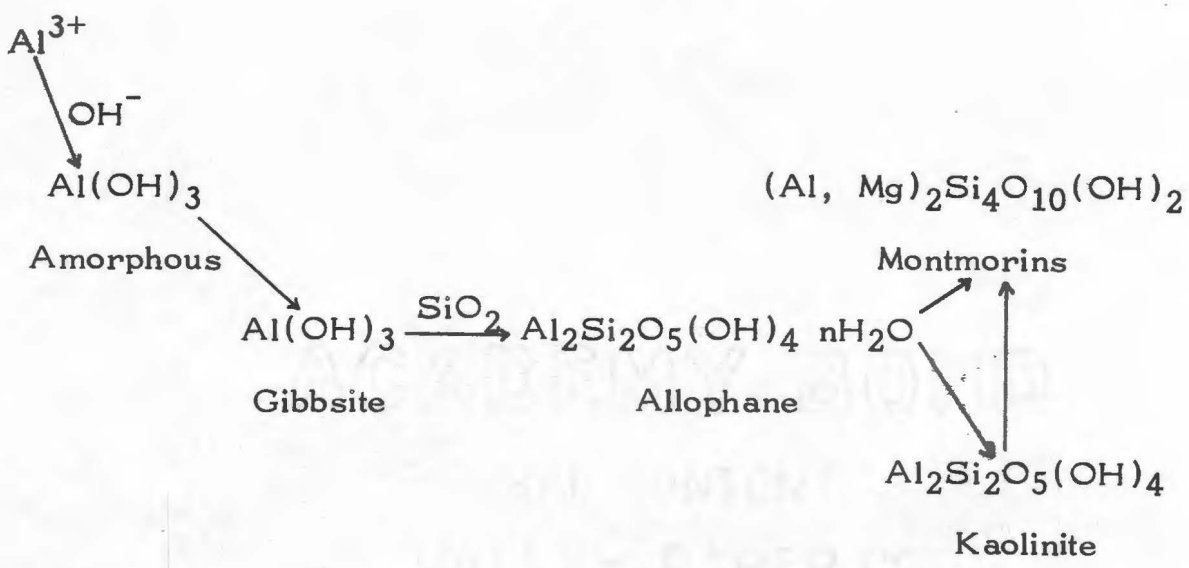
Recently, the subject matter of amorphous mineral colloids, which is a main constituent of the soils formed from volcanic ash

is extensively reviewed by Kanehiro and Whittig (1961), Mitchell, Fermer and McHardey (1964) and Fieldes (1966).

Tamura et al. (1953) placed allophane in Jackson's weathering sequence (1953), along with gibbsite and boehmite in the 11th stage, whereas kaolinite and halloysite in the 10th stage and hematite, limonite and goethite in the 12th stage.

Fieldes and Swindale (1954) presented a sequence for the weathering of the minerals present in the soils and the rock. According to them feldspars as well as volcanic glass gets converted to amorphous hydrous oxides and this in turn to allophane and then to kaolin minerals. They also said that orthosilicates and basic glass weather rapidly. Slightly slower weathering is shown by pyroxenes and hornblende. Acid volcanic glass and feldspar weather still slower. The mechanism by which these weather may be called solution - precipitation - crystallization transformation. According to these workers, the nature of the mineral formed in any soil can be predicted if its parent material and the weathering stage are known.

Tamura and Jackson (1953) proposed a system of structural and energy relationship of iron and aluminum oxides, hydroxides and silicates showing a sequence of conversion of ionic elements to crystalline minerals through an intermediate of amorphous mineral colloids.



(According to the authors, downward slope of arrows indicative of ease of reaction occurrence.)

Fieldes (1955, 1956 and 1957) by studying the mineralogy of the clays derived from rhyolite and andesitic ash, subdivided the allophane into allophane A, allophane B, and allophane AB and proposed the following sequence of weathering: allophane B (amorphous silica and alumina are discrete; ultra-fine-particle size) ⟶ allophane A (co-precipitated silica and alumina; larger particle size) ⟶ metahalloysite ⟶ kaolinite.

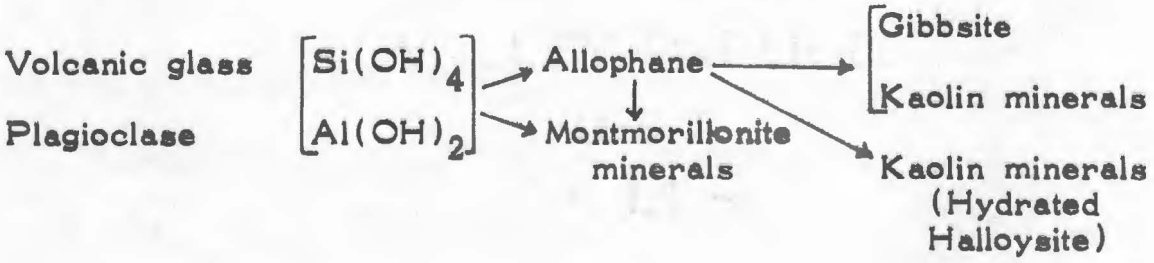
In studying the differential weathering of volcanic ash and pumice, Aomine and Wada (1962) proposed an order of the relative stability of the primary minerals to weather. The stability increases in the following order: Volcanic glass < feldspar < hypersthene -augite < magnetite. They also came to the conclusion (andesine-Labradorite)

that volcanic glass and feldspars weather to allophane and this in turn to hydrated halloysite. This sequence is similar to the one

obtained by Fieldes and Swindale (1954). Aomine and Wada (1962), also suggested a mechanism for the formation of the minerals in their sequence. Their steps in the mechanism are:

1. Partial hydration of volcanic glass or feldspar leading to alteration of O linkage to OH and resulting in release of some Si and metallic cations.
2. Rearrangement of the remaining Al and Si together with associated O, OH, H_2O, in situ. Prevailing chemical conditions adjust the composition of the resulting silica-alumina system.
3. Formation of a gibbsite-like structure with some adsorbed SiO_4 tetrahedra.
4. Replacement of OH groups by O on further addition of SiO_4 tetrahedra or on the condensation resulting in dehydroxylation.
5. Re-orientation of SiO_4 tetrahedra.

Kanno (1962) presented a scheme for the formation of main clay minerals from volcanic ash soils in Japan:



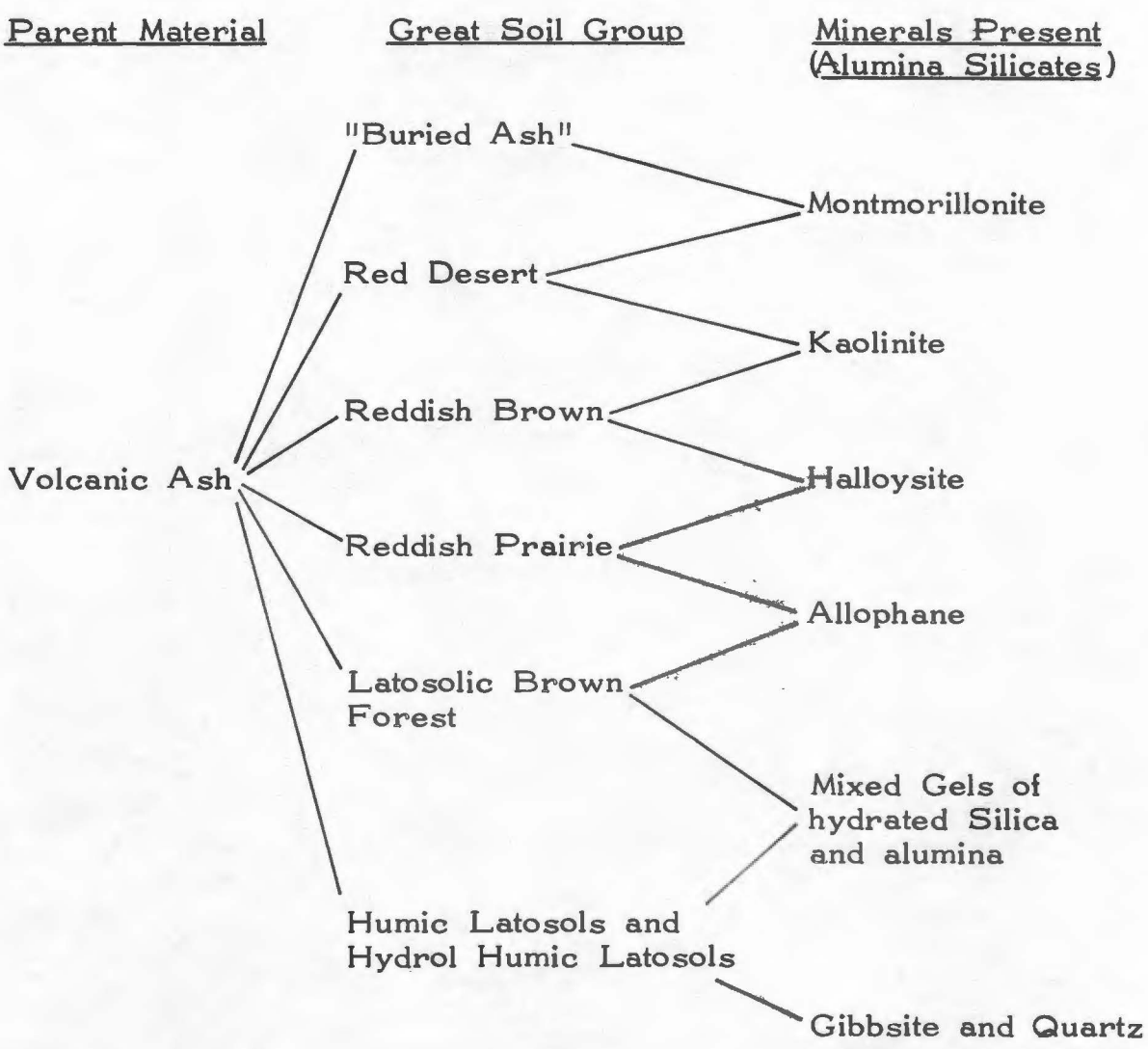
The formation of montmorillonite was also observed in many other places. According to Grim (1958), volcanic ash high in

magnesium tend to form montmorillonite, but those low in this element go to allophane and kaolin minerals.

Bates (1960), in studying mineral alterations in the Hawaiian Islands, came to the conclusion that weathering in Hawaii is largely a process of desilication. He also mentioned that gibbsite forms in at least three ways in Hawaii: (1) By removal of silica from halloysite, (2) by dehydration of aluminum and iron gels, and (3) by precipitation from Al-rich solutions. Type (2) is possibly due to either surface exposure or due to dry climates. Sherman (1957) has also pointed out that on air drying the amorphous fraction of H.H.L. and other soils developed on andesitic ash, gibbsite crystallizes and separates out.

An amorphous colloidal mineral called palagonite is also commonly found in volcanic ash soils. This may be formed by the weathering of basaltic glass under conditions of restricted leaching (Birrel, 1964). It is similar to allophane in its tendency to form aggregates, but less finely divided than allophane. Chemically it resembles montmorillonite. This amorphous colloid is also found in some parts of Pahala ash in Hawaii (Stearns and Macdonald, 1946).

A scheme for the formation of secondary aluminum silicate minerals present in different Hawaiian soils derived from volcanish ash was presented by Houng (1964).



Chemical Properties

Soils derived from volcanic ash have peculiar properties due to the high reactivity of the amorphous fraction which possesses a high specific surface charge. Studies on Japanese soils summarized in "Volcanic Ash Soils of Japan" (1964) indicate that these soils could have high content of organic matter (up to 30%) and very high C/N ratio (up to about 24), particularly in the top soils.

Cation exchange capacity of these soils are also found to be high. Fieldes, Swindale and Richardson (1952) found that the cation exchange capacity of some soils of the Lower Cook Islands group is due mainly to amorphous colloidal hydrous oxides. White (1953) obtained a value of 69 to 73.5 m.e. per 100 gm for the cation exchange capacity of allophane whereas Aomine and Yoshinaga (1955) and Birrel and Fieldes (1952) obtained values of 23.3 to 57.3 and 54 m.e./100 gm respectively. Birrel and Gradwell (1956) found that the cation exchange capacity of allophanic soils varied with the (1) concentration of the leaching solution, (2) nature of ions in solution, and (3) the volume of water content of the washing alcohol. Kanehiro and Sherman (1956) have shown that certain Hawaiian soils having high amounts of amorphous material lost cation exchange capacity on drying and did not regain their cation exchange capacity on rewetting. This is due to crystallization of constituents of the amorphous fraction on drying.

The pH values of volcanic ash soils are usually above 5.0. It is unusual to find pH values below this owing to the strong buffering capacity of allophane in the region of its iso-electric point or the strong buffering capacity of polymerized alumina gels (Swindale, 1964; Birrel, 1964).

Birrel (1964) mentioned that the base saturation of allophane could be very low, even though the pH values indicate only weak

to moderate acidity. Swindale (1964) pointed out that the estimation of base saturation of allophanic soils is unreliable since the amorphous mineral colloids have pH dependent charge and the base saturation measured in the laboratory at pH 7 may be much lower than the actual base saturation of the soil in its field condition at a lower pH.

Physical Properties

Birrel (1964) mentioned that these soils have a very high moisture content throughout the profile and have a very low bulk density value. This high moisture content is also found in Hawaiian soils derived from volcanic ash by Kanehiro and Sherman (1956) and Houng (1964). Swindale pointed out that in Hawaii, they found a highly significant regression of field moisture content upon organic matter content in Hydrol Humic Latosols.

Birrel (1964) has said that the particle size distribution of soils derived from volcanic ash has not much meaning due to the presence of (1) amorphous colloids which have a high iso-electric point and (2) hydrous oxides which induce mutual co-precipitation.

Climate as a Soil Forming Factor

Climate has been known to be a most important soil forming factor from the early days of the study of soil formation. Different soil forming factor equations were published beginning with Dokuchaev in 1898 who presented equations of the form:

$$S = f(cl,\ O,\ p)$$

$$S = f(cl,\ O,\ p)t^{o}$$

where S represents soils, cl climate of a given region, O the organisms, p the geologic substratum and t^{o} relative age. The relief factor was omitted in these equations.

In 1941, Jenny developed an equation of the form

$$S = f(cl,\ O,\ r,\ p,\ t)$$

where the dependent variable S denotes any soil property and the independent variables within the parentheses are the soil forming factors, mostly group of factors defined as follows:

cl: environmental climate

O: organisms and their frequencies referring to the total disseminules rather than actual growth

r: topography, also including certain hydrological features (e.g. water table)

p: parent material, defined as state of soil at soil formation time zero

t: age of soil, absolute period of soil formation

---: additional unspecified factors

This functional equation can be written in the form of a differential equation:

$$dS = \left(\frac{\partial S}{\partial cl}\right)_{o,p,r,t} dcl + \left(\frac{\partial S}{\partial o}\right)_{cl,p,r,t} do + \left(\frac{\partial S}{\partial r}\right)_{cl,p,o,t} dr + \left(\frac{\partial S}{\partial p}\right)_{cl,o,t,r} dp + \left(\frac{\partial S}{\partial t}\right)_{cl,o,p,r} dt \quad \ldots$$

or

$$dS = \sum \left(\frac{\partial S}{\partial x_i} \right)_{[x_i]'} dx_i \qquad [x_i]' : \text{ the factors other than } x_i$$

In this equation it is assumed that all the soil forming factors are independent variables and the soil property (S) is the dependent variable. This is an equation relating a change in a soil property brought about by a change in one or more of the primary soil forming factors.

Later on, in 1946, Jenny modified his equation by defining the soil property as a function of a single factor keeping the other factors constant.

$S = f_{cl}(\text{climate})_{o,r,p,t \ldots}$ Climofunction

$S = f_{o}(\text{organism})_{cl,r,p,t \ldots}$ Biofunction

$S = f_{r}(\text{topography})_{cl,o,p,t \ldots}$ Topofunction

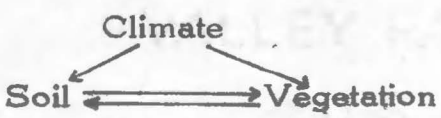
$S = f_{p}(\text{parent material})_{cl,o,r,t \ldots}$ Lithofunction

$S = f_{t}(\text{time})_{cl,o,r,p \ldots}$ Chronofunction

Due to criticism from Crocker (1952) and others, Jenny in 1958 discussed the interplay of climate, soil and vegetation and changed his equation into

$$V,S = f(cl,t,r,p \ldots)$$

or



It implies that climate affects soil and vegetation independently, that

soil influences vegetation, and that vegetation reacts upon soil.

Jenny in his recent paper (1961) further modified his state factor equation into

$$l,s,v,a = f(L_o, P_x, t)$$

where ecosystem properties are represented by l, soil properties by s, vegetation properties by v, animal properties by a. These properties are function of the three state factors: initial state of the system L_o (namely its assemblage of properties at time zero, when genesis starts); external flux potentials P_x, and age of the system t.

Although there are many changes and controversies in Jenny's original equation, it is easy to handle and can be used for practical purposes. In the field it is very difficult to satisfy the required constancy of factors. Useful approximations to single-factor functions within a given area can be obtained if the change in soil property due to one factor greatly exceeds that of the others. This condition can be obtained in two ways:

1. Relative variation of one of the factors is very much greater than the others.
2. Some factors may vary considerably, yet be of relatively little importance in determining differences in soil properties; i.e. the change in soil property with change in a soil forming factor is nearly zero, although the change in soil property is not zero.

In a climosequence, for all the other state factors except for climate either $\left(\frac{\partial S}{\partial x_i}\right)_{[x_i]'}$ or dx_i is zero. Then $dS = \sum_{1}^{n}\left(\frac{\partial S}{\partial x_i}\right)_{[x_i]'} dx_i$ becomes $dS = \left(\frac{\partial S}{\partial cl}\right) dcl$.

Since climate essentially depends on temperature and rainfall and temperature are independent of each other, this can be expressed as:

$$dS = \left(\frac{\partial S}{\partial r}\right)_t dr + \left(\frac{\partial S}{\partial t}\right)_r dt$$

If numerical values can be found for the unknowns in these equations, the study of soil formation can be made quantitative.

The effect of climate on soil properties have been studied by many workers in Hawaiian soils.

Tanada (1952) on working with a number of soils, some of them derived from volcanic ash, came to the conclusion that kaolin decreases with increasing rainfall. He also found that SiO_2/Al_2O_3 and SiO_2/Fe_2O_3 decreases with increasing rainfall.

The influence of rainfall on the cation exchange capacity and base saturation of a number of Hawaiian soils was studied by Ayres (1943), Kanehiro and Chang (1956). These properties were found to decrease with increase of rainfall. It is generally found that base saturation decreases with increase of rainfall in volcanic ash soils (Swindale and Sherman, 1964).

Dean (1937) found that carbon and nitrogen increase with

increasing rainfall and decrease with increasing temperature. He also found that carbon-nitrogen ratio increases with increasing rainfall. Ayres (1943), Blomberg and Holmes (1959) also found the same type of trends for carbon, nitrogen and carbon-nitrogen ratio with rainfall.

In all of the above work on the effect of climate with properties, the effect of other soil forming factors were not constant for all the soils. Jenny (1941) in his book on "Factors of Soil Formation" presented the single factor effect of climate on several soil properties.

Classification of Andepts

Different workers have used different types of classification for the soils derived from volcanic ash. Swindale and Sherman (1964) in their paper on volcanic ash sites of Hawaii presented a classification of Hawaiian soils according to Cline (1955), the S.C.S. 7th Approximation (1964) and Taylor and Pohlen's New Zealand system (1962).

In the very recent, and as yet unpublished comprehensive soil classification system (Oct. 1966), the S.C.S. has modified the 7th Approximation. In this classification system, andepts are considered to be a suborder of inceptisols. The prefix And is derived from the earlier Japanese-derived name Andosols (An meaning dark and do meaning soil). The prefix ept is derived from the order name inceptisol. In the recent classification (Oct. 1966) andepts are defined as inceptisols that

(1) have one or both of (a) a bulk density (at field capacity) of the fine earth fraction of the soil of less than 0.85 gm per cm^3 in the epipedon or the cambic horizon, or both, and an exchange complex that is dominated by amorphous material, or (b) more than 60% of Vitric volcanic ash, pumice or other pyroclastic material in the silt, sand and gravel fraction, (2) are not saturated with water at any season or lack the characteristics associated with wetness defined by aquepts, and (3) lack a plaggen epipedon.

The suborder andept is divided into six great groups on the basis of the kind and arrangement within the soil profile of certain criteria either "diagnostic horizons" or base saturation, moisture retention, organic matter, soil temperature, color or other properties related to climate. The chief characteristics which differentiate these great groups are given below:

1. Cryandepts: Andepts with low mean annual temperature
2. Durandepts: Other andepts with duripan
3. Dystrandepts: Other andepts which have an umbric or ochsic epipedon with fine to medium texture and 15-bar water retention greater than 20% based on the average of the whole soil
4. Vitrandepts: Other andepts with coarse texture and 15-bar water retention 20% or less based on the average of the whole soil
5. Eutrandepts: Other andepts with mollic epipedons with

texture and 15-bar water as for Dystrandepts

6. Hydrandepts: Other andepts with clays that dehydrate irreversibly into gravel-size aggregates

These great groups are subdivided into subgroups. Each great group is believed to have one central subgroup which reflects the central concept of that great group. This central subgroup is always named the Typic subgroup. Most of the other great groups integrade towards other great groups, sub-order or orders and therefore they are named according to the category to which they grade.

THE SOILS

Location of the Sampling Sites

The samples were collected on the northern slopes of Mauna Kea from an elevation of 6900 feet to 3400 feet. The approximate locations of the sample sites and the extent of the ash in this region according to the geological map prepared by Stearns and Macdonald (1946), are shown in Figure 1. According to this map, Maile and Umikoa are derived from the ash near the Kohalatite Gulch and Apakuie is derived from the ash close to the Kapoholemuele Gulch. The location for Hanaipoe according to this map shows that it is formed on andesite and basaltic lava flows of the lower member of Laupahoehoe volcanic series. The other three soils are derived from andesitic ash overlying the lava flows. However, at the site there is little doubt that the Hanaipoe soil is also formed from ash. The lava flows are of the age of Hamakua Volcanic series or even younger.

Apakuie was collected at 19° 54' 45" North latitude and 155° 23' 30" East longitude from a pit located about 1.5 miles north of Puu Kihe above Kukaiai Ranch and about 2 miles west of forest reserve headquarters. Hanaipoe soil was collected in Kukaiai Ranch at 19° 56' 38" North latitude and 155° 23' 53.5" East longitude from a pit located 1/2 mile south of the nearest water tank. Umikoa soil sample was also collected in the Kukaiai Ranch at 19° 58' 12.4" North latitude and 155° 22' 50.5" East

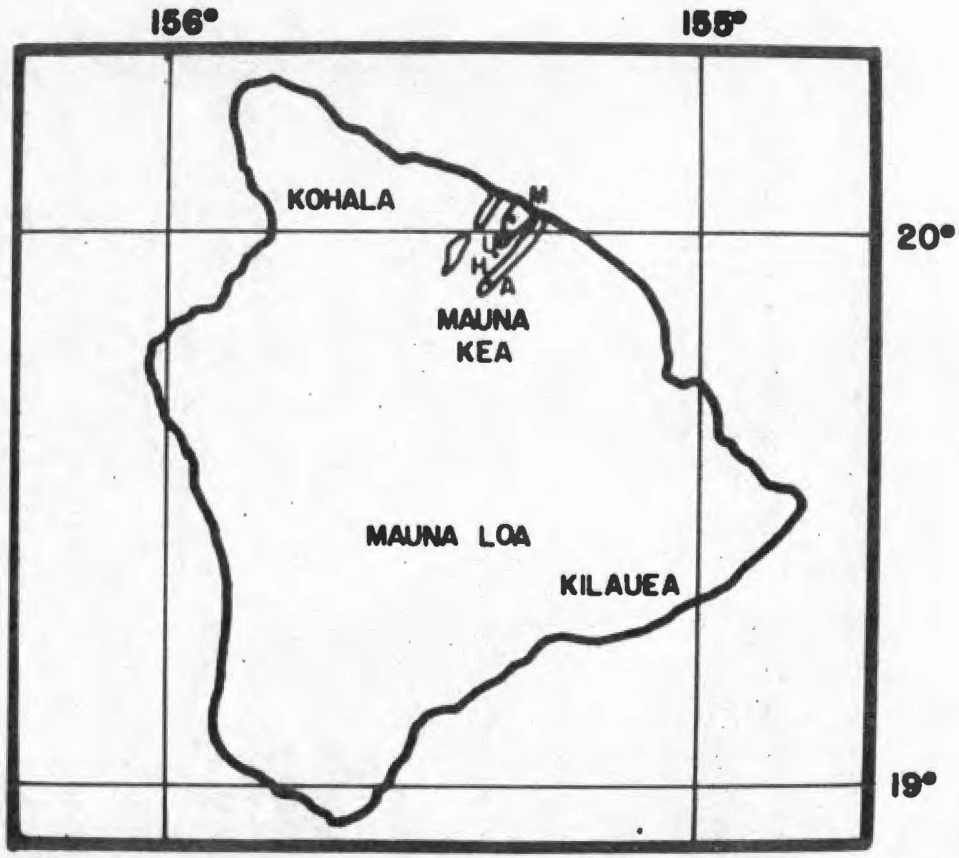


Figure 1. Map of the Island of Hawaii, Showing the Location of Sampling Sites and Extent of the Ash.
A: Apakuie; H: Hanaipoe; U: Umikoa; M: Maile

longitude. This place is located approximately 1/2 mile south of Umikoa village. Maile soil was collected at 19° 59' 10" North latitude and 155° 23' 10" East longitude from a pit located 1/2 mile east of Umikoa village and 100 yards west of the paved road.

Environment of the Soils

Genetic factors and general information about the four soils are shown in Table 1. Median annual rainfall was determined from the closest rainfall gauges to the soil sites. Median annual rainfall was measured for several years and presented by Hawaii Water Authority (Taliaferro, 1959). Statistical investigation (Landsberg, 1951) suggests that due to the skewed frequency distribution, rainfall means are misleading and medians are preferred for climatological purposes. Medians reach stability after 3 to 5 decades usually long before means and might serve as "normals".

Soil temperature at a depth of 50 inches was taken as the average annual temperature. Usually the temperature decreases with a constant rate as the altitude increases. The temperatures of Maile and Umikoa are found to be the same. This may be due to the temperature inversion which takes place at heights between 4,000 feet and 8,000 feet above sea level. At the inversion, the temperature increases by several degrees, sometimes quite suddenly. These higher temperatures may extend

Table 1. Genetic Factors of the Soils

Soils	Apakuie	Hanaipoe	Umikoa	Maile
Classification	Eutric Vitrandepts -L.B.F	Typic Normandepts -L.B.F	Hydric Normandepts -L.B.F	Hydric Normandepts -L.B.F
Vegetation	Mamani grass cover	Pasture	Pasture	Ohia grass cover
Parent Material	Volcanic ash	Volcanic ash	Volcanic ash	Volcanic ash
Elevation	6900'	5100'	4350'	3400'
Slope	10%	5%	6%	Convex
Erosion	Slight	Slight	Slight	Slight
Drainage	Well drained	Well drained	Well drained	Well drained
Rainfall	24"	42"	55"	72"
Soil Temperature				
at 50"	55°F	62°F	65°F	65°F
at 20"	55°F	64°F	67°F	

upward for several hundreds of feet before the temperature begins once more to decrease upward in the manner that is most usual in the atmosphere (Blumenstock, 1961). In these areas where the soils were collected, weather is cloudy and foggy throughout the year. All these soils are well drained and have similar slopes.

Description of the Soils

The various profiles were described by different persons. Apakuie soil profile was described by H. Sato, Hanaipoe and Umikoa by Dr. L. D. Swindale, and Maile by H. Sato and L. D. Giere. These descriptions are given below:

Apakuie Very Fine Sandy Loam

Horizon	Depth	Description
A1	0-2"	Dark reddish-brown (5YR 2/2) loam, yellowish brown (10YR 5/4) dry; granular structure; friable, nonsticky and nonplastic; abundant roots; many fine pores; neutral (pH 6.8); abrupt smooth boundary.
B2	2-8"	Yellowish-red (5YR 4/6) very fine sandy loam, strong brown (7.5YR 5/6) dry; massive; friable, nonsticky and nonplastic; abundant roots; few stones; many very fine pores; neutral (pH 7.0); abrupt wavy boundary.

Horizon	Depth	Description
IIAb	8-15"	Dark reddish-brown (5YR 3/2) very fine sandy loam, yellowish brown (10YR 5/4) dry; massive; friable, nonsticky and nonplastic; plentiful roots; many very fine pores; 5 percent by volume of stones larger than 3/4-inch diameter; neutral (pH 6.8); clear wavy boundary.
IIC1	15-30"	Dark reddish-brown (5YR 3/3) very fine sandy loam, strong brown (10YR 5/6) dry; massive; friable, nonsticky and nonplastic; few roots; many very fine pores; 5 percent by volume of stones larger than 3/4-inch diameter; neutral (pH 6.8); gradual wavy boundary.
IIC2	30-50"	Dark reddish-brown (5YR 3/3) loamy sand, strong brown (10YR 5/6) dry; weak coarse prismatic structure; friable, nonsticky and nonplastic; few roots; many very fine pores; 10 percent by volume of stones larger than 3/4-inch diameter; neutral (pH 6.8).

Hanaipoe Silt Loam

Horizon	Depth	Description
Ap1	0-5"	5YR 2/2 silt loam; weak fine granular structure; friable, nonsticky slightly plastic; many roots; many very fine pores; abrupt smooth boundary.
Ap2	5-10"	10YR 2/2 silt loam; weak very fine granular structure; friable, nonsticky slightly plastic; many roots; many fine pores; abrupt wavy boundary.
		Pockets of red material which is very friable and contain pieces of charcoal, 2.5YR 3/4 very fine sandy loam.
B21	10-18"	7.5YR 3/4 silt loam; weak medium and fine subangular blocky structure; friable, slightly sticky slightly plastic; many roots; many fine pores; gradual wavy boundary.
B22	18-31"	5YR 2/2 silt loam; weak medium subangular blocky; friable; slightly sticky slightly plastic; many very fine pores; many roots; abrupt smooth boundary.
B23	31-40"	10YR 3/3 silt loam; weak medium subangular blocky; friable; slightly sticky plastic; many roots; many fine pores; abrupt

Horizon	Depth	Description
		wavy boundary.
C	40-43"	10YR 2/1 compacted sand; massive structure; friable nonsticky nonplastic; few roots; abrupt smooth boundary.
B24b	43-60"	7.5YR 2/2 silt loam; weak medium subangular blocky structure; friable slightly sticky plastic; many roots; many very fine pores.

Umikoa Silty Clay Loam

Horizon	Depth	Description
Ap	0-10"	5YR 2/2 silt loam; weak very fine granular structure; friable; nonsticky nonplastic; many very fine pores; matted roots; abrupt smooth boundary.
B21	10-18"	7.5YR 3/2 silty clay loam; moderate medium and fine subangular blocky structure; friable; many roots; many very fine pores; abrupt smooth boundary.
C	18-28"	10YR 3/2 silty clay loam; weak medium subangular blocky structure; friable compact in place; sticky plastic; many very fine pores; roots flattened many between peds; abrupt smooth boundary.

Horizon	Depth	Description
B22b	28-43"	7.5YR 3/2, 10YR 2/2 varigated silty clay loam; moderate medium and fine subangular blocky; friable; slightly sticky plastic; many very fine pores; roots common; abrupt wavy boundary.
B23b	43-52"	7.5YR 3/2 silty clay loam; moderate medium and fine subangular blocky; friable; sticky plastic weakly smeary; many medium and fine pores; roots common; abrupt smooth boundary.
B24b	52-60"	10YR 3/2 silty clay loam; weak medium and fine subangular blocky structure; friable; sticky plastic weakly smeary; many weak and fine pores; few roots.

Maile Silt Loam

Horizon	Depth	Description
A11	0-2"	Very dusky red (2.5YR 2/2) silt loam;
S65Ha-1-7-1		moderate fine granular structure; friable, nonsticky and slightly plastic; abundant roots; many fine pores; abrupt smooth boundary.
A12	2-4"	Dark brown (10YR 3/3) cindery sandy
S65Ha-1-7-1		loam; moderate fine granular structure;

Horizon	Depth	Description
		friable, non-sticky and non-plastic; abundant roots; common fine black cinders and charcoal; abrupt smooth boundary.
AI3	4-14"	Very dark brown (10YR 2/2) silty clay
S65Ha-1-7-2		loam; strong fine subangular blocky structure; hard, friable, slightly sticky, plastic and weakly smeary; abundant roots; many fine pores; clear wavy boundary.
IIB21	14-17"	Dark yellowish brown (10YR 3/4) silty
S65Ha-1-7-3		clay loam; weak coarse prismatic breaking to moderate fine subangular blocky structure; friable, slightly sticky, plastic and weakly smeary; abundant roots; many fine pores; clear smooth boundary.
IIIB22	17-20"	Dark brown (10YR 3/3) silty clay loam;
S65Ha-1-7-3		weak coarse prismatic breaking to moderate fine subangular blocky structure; friable; sticky, plastic and weakly smeary; plentiful roots; many fine pores; clear smooth boundary.
IVB23	20-24"	Dark yellowish brown (10YR 3/4 silty
S65Ha-1-7-3		clay loam; weak coarse prismatic breaking to moderate fine subangular blocky structure;

Horizon	Depth	Description
		friable, sticky, plastic and weakly smeary; few roots; clear smooth boundary.
VC S65Ha-1-7-3	24-29"	Dark brown (10YR 3/3) silty clay loam; massive; hard, firm, slightly sticky, slightly plastic and weakly smeary; tuff band; few roots; many fine pores; abrupt smooth boundary.
VIB24 S65Ha-1-7-4	29-36"	Dark brown (7.5YR 3/4) silty clay loam; weak medium and fine subangular blocky structure; friable, sticky, plastic and moderately smeary; common patchy glaze; few roots; many fine pores; abrupt smooth boundary.
VIIB25 S65Ha-1-7-5	36-48"	Very dark brown (10YR 2/2) silty clay loam; yellowish brown (10YR 5/6) dry; weak coarse and medium prismatic breaking to strong medium and fine sub-angular blocky structure; friable, sticky, plastic and moderately smeary; common patchy glaze; tuff band about 2 inches thick; few roots; many fine pores; neutral (pH 6.6) abrupt smooth boundary.

Horizon	Depth	Description
VIIIB26	48-60"	Very dark brown (10YR 3/2) silty clay loam; weak medium subangular blocky structure; friable, sticky, plastic and smeary.
S65Ha-1-7-6		

*Combined samples of [A11, A12] and [IIB21, IIIB22, IVB23, VC] were used for all analyses.

METHODS

Sample Preparation

The freshly collected field samples were crushed gently with a wooden roller and sieved through a 2 mm sieve. The sieved sample was thoroughly mixed and subsampled. One subsample was air-dried and further ground to pass through 100 mesh sieve, thoroughly mixed and stored in bottles for carbon, nitrogen, free iron oxide and differential thermal analyses. These volcanic ash soils which contain amorphous colloids have the property of irreversible drying and change some properties if dried. To prevent this, all the rest of the subsamples were stored in double plastic bags in field moist condition. This moist soil was used for the determination of pH, cation exchange capacity and particle size distribution.

For effective dispersion and fractionation of the soils into different size fractions, soluble electrolytes, divalent metallic cations, chemical cements such as organic matter, free iron oxides and colloidal silica and alumina were removed according to Jackson's (~~1965~~ 1956) method.

About 15 gms of the field moist sample was acidified with neutral NaOAc buffered at pH 5 to remove carbonates and exchangeable cations and then treated with H_2O_2 (technical grade) for the removal of organic matter and the dissolution of MnO_2. Removal of organic matter was carried out for a long time, due

to the slow rate of decomposition of organic matter in volcanic ash soils. Complete removal of soluble salts and exchangeable bases was carried out by several washings with 95 percent and 99 percent methanol. Free iron oxides were removed according to the sodium dithionite-citrate-bicarbonate method presented by Aguilera and Jackson (1953). The soil was then boiled for five minutes in 2 percent Na_2CO_3 (pH 10.5) to remove the free silica and alumina and finally dispersed in distilled water. The sands were separated by wet sieving using a 325 mesh sieve (43 microns). The silts (50μ - 2μ), coarse clay (2μ - 0.2μ) and fine clay (<0.2μ) were separated by sedimentation and centrifugation techniques. The sand and silt fractions were dried, weighed and stored in glass vials for X-ray and Petrographic analyses.

Mineralogical Analyses

Petrographic Analyses

The sands and silts of selected samples were examined under the petrographic microscope. Special attention was given to the presence of plant opal and glass shards which cannot be detected by other methods.

X-ray Diffraction Analyses

X-ray diffraction patterns were obtained using a Philip-Norelco X-ray Diffractometer with Cu radiation. Sand and silt fractions were X-rayed using a random oriented powder mount. The clays to be investigated were saturated with potassium by

washing it several times with N potassium chloride and then with an alcohol-water mixture to remove the excess potassium chloride. Parallel oriented slides were obtained by drying the clays on the glass slides. Due to the high amount of amorphous material, the clays tend to curl up when dried on the glass slide. To prevent this one drop of 50 percent glycerine was added on the glass slide before pipetting 1 ml. of approximately 1 percent clay suspension on it. The K-saturated parallel oriented clays were X-rayed at room temperature. Some of these slides were heated in a muffle furnace at 350°C and 550°C respectively for three hours and X-rayed. In some cases the clays were saturated with magnesium by washing several times with N magnesium chloride and then washing with water-alcohol mixture to remove the excess salt. The clays were dispersed in water and dried in parallel orientation on glass slides. This air dried slide was glycolated by keeping it in ethylene glycol environment for three hours at 70°C. This magnesium-saturated glycolated sample was X-rayed at room temperature.

Differential Thermal Analyses

Air-dried whole soil was ground to pass through 100 mesh and kept for three days in a vacuum desiccator saturated with $Mg(NO_3)_2$ to keep the relative humidity at about 52 percent. 0.10 gms of the whole soil was thoroughly mixed with 0.09 gms of calcined alumina and analyzed with a Stone Automatic D.T.A.

machine at the rate of 10°C per minute from 25°C to 1050°C. Selected clays were also analyzed. The reference sample was calcined alumina. Nitrogen gas was used to suppress the oxidation of organic matter. The intensity of the first endothermic peak was reduced by using 0.57 millivolts in the initial stages of the analyses (up to 210°C). For the remainder of the analyses 0.285 millivolts was used. The areas of the first endothermic peaks were measured by means of a planimeter.

Chemical Analyses

Soil pH

Soil pH was measured with both H_2O (1:5) and KCl (1:5) using a Beckmann pH meter. The solution is kept overnight in a constant temperature room at 22°C with occasional shaking, and the pH of the suspension was taken 40 secs. after stirring with the electrodes.

Organic Matter

Air dried 100 mesh soils were used for organic matter determination. Readily oxidizable organic matter is oxidized by chromic acid in the presence of concentrated sulphuric acid and the excess of chromic acid not used for oxidation is back titrated with ferrous sulphate. Here the heating is obtained by the spontaneous heat evolved by the dilution of concentrated H_2SO_4 (Walkley and Black, 1934). A recovery factor of 77 percent was used. The amount of organic matter was determined by

multiplying the organic carbon by a factor of 1.724.

Free Iron Oxides

Air dried 100 mesh soils were used to determine free iron oxides by the modified Kilmer's method (1960). The iron oxides reduced by dithionite method was determined by titration with potassium dichromate.

Total Nitrogen

Total nitrogen in 100 mesh soils were determined by means of Kjeldahl's method. In this method the organic matter is oxidized by concentrated H_2SO_4 in the presence of potassium sulphate, ferrous sulphate and copper sulphate and the nitrogen converted to ammonia. The ammonia and sulphuric acid formed ammonium sulphate. Ammonia in the ammonium sulphate is distilled into boric acid and the ammonium borate formed was titrated with standard H_2SO_4 using methyl red, methylene blue mixed indicator.

Cation Exchange Capacity (C.E.C.)

Cation exchange capacity was determined on field moist soils (20 mesh) by using N NH_4OAc buffered at pH 7 to saturate the soil with NH_4 ions. Excess NH_4 ions were washed down by methyl alcohol. Four percent KCl was used to exchange the NH_4 ions adsorbed in the exchange sites. The replaced NH_4 ions were distilled with 1:1 NaOH and the ammonia evolved was absorbed in 4 percent boric acid and titrated against standard H_2SO_4 using methyl red, methylene blue mixed indicator.

Exchangeable bases such as Ca^{++}, Mg^{++}, K^{+} and Na^{+} were determined from the NH_4OAc leachate of the soils. Exchangeable Ca was determined by precipitating CaC_2O_4 using $(NH_4)_2C_2O_4$ and titrating it with 0.05 N $KMnO_4$ in the presence of H_2SO_4. Exchangeable Mg was precipitated as $MgHPO_4$ by the addition of diammonium phosphate. $MgHPO_4$ is converted to magnesium ammonium phosphate by careful addition of ammonium hydroxide. The precipitated magnesium ammonium phosphate was ignited and weighed as magnesium pyrophosphate. Exchangeable sodium and potassium were determined by means of Beckman DU flame photometer.

Physical Analyses

Particle Size Distribution

Particle size distribution was done following Jackson's method (1964).

15-Bar Water

15-bar water was determined by using the pressure membrane apparatus. Soil samples were packed on the pressure plate in rubber rings and saturated overnight with water from the bottom. The soils were then subjected to a 15-bar pressure and allowed to reach equilibrium. Two to three days were required for equilibrium. A few gms of the soil was weighed immediately and after oven-drying to find the percent moisture at 15-bar pressure.

RESULTS

Petrographic Analyses

Sand and silt fractions were analyzed using the petrographic microscope. Main minerals identified are feldspars, opaque minerals, olivine, pyroxenes, volcanic glass, aggregates of non-dispersible clay, and plant opal.

Feldspar grains were mostly seen in Apakiue and found to decrease with increase of rainfall in the sequence. They had strong cleavage and some of them showed a type of twinning that appears as alternate dark and light bands in cross polarized light. The magnetite grains are opaque and found to be present in all the soils. Highly birefringent olivines with uneven to conchoidal fracture were also seen. Hanaipoe contained more olivine than the other soils. The pyroxene grains were mainly augite with an extinction angle of approximately 45°. Augite is mainly found in Umikoa and Maile.

Plant opal is present in almost all soils, mainly in the silt fraction and surface horizons. Hydrogen peroxide treatment has not destroyed it. In some cases, plant opal was found to be abundant in deep horizons showing the presence of buried A horizons. Opal being isotropic becomes dark and hence invisible under crossed nicols. The plant opals are similar to those found by Houng (1964) in similar soils from the slopes of Mauna Kea and by Smithson (1958) in British soils. Smithson (1958)

found large amounts of grass opal in British soils under pasture cover and described their morphology. He concluded that these plant opals found in the soils are formed from the leaves of the grasses. Presence of these opals in the soils under study shows that there is active growth of grasses in this area.

X-ray Diffraction

X-ray diffraction patterns of the individual horizon samples are interpreted and summarized schematically in Tables 2-6. Selected patterns are presented in Figures 2-5. Each mineral identified in a given sample has been assigned a grade value to denote its significance relative to the other components present. This value has no qualitative bearing but provides a means by which to compare differences within a profile and in the sequence. Evaluation of the grade value is in accordance with the relative peak intensities.

X-ray diffraction patterns of the coarse fraction gave strong diffraction peaks of feldspars (3.20 Å) and moderate peaks of spinel type iron oxide minerals of the magnetite-maghemite series (2.52 Å) and quartz (3.34 Å). Very weak diffraction peaks of olivine and ilmenite were also detected in some of the horizons. Some weakly formed secondary minerals such as gibbsite and layer silicates were also identified in a few instances, probably due to incomplete dispersion of the clay.

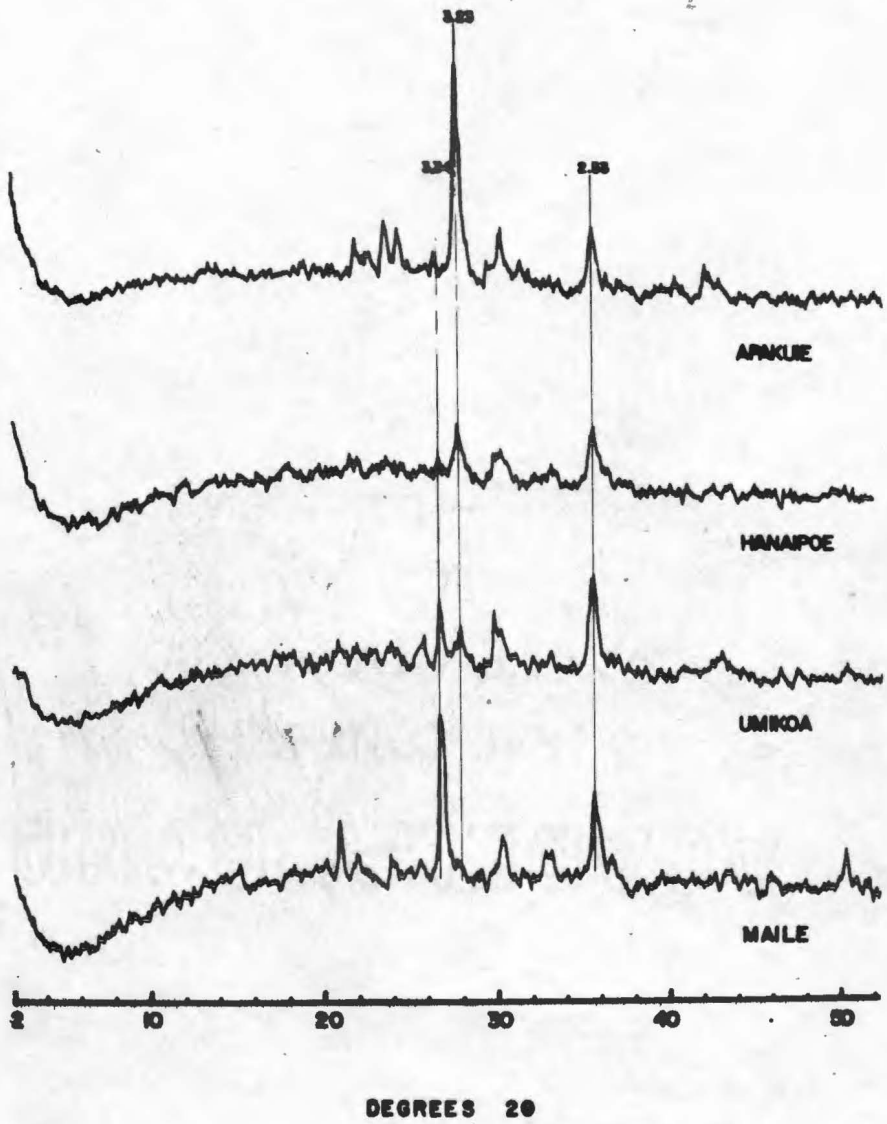


Figure 2. X-ray Diffraction Patterns of the Silt Fraction of Surface Horizon

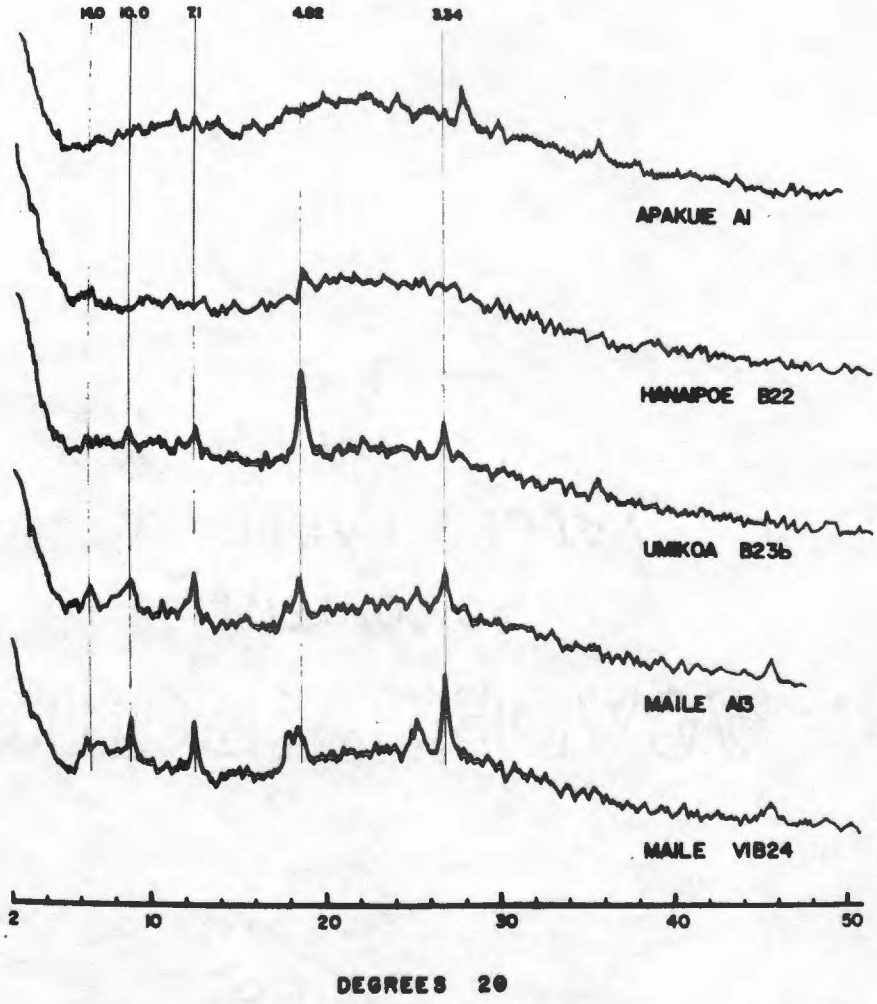


Figure 3. X-ray Diffraction Patterns of Selected Coarse Clays (2μ - 0.2μ)

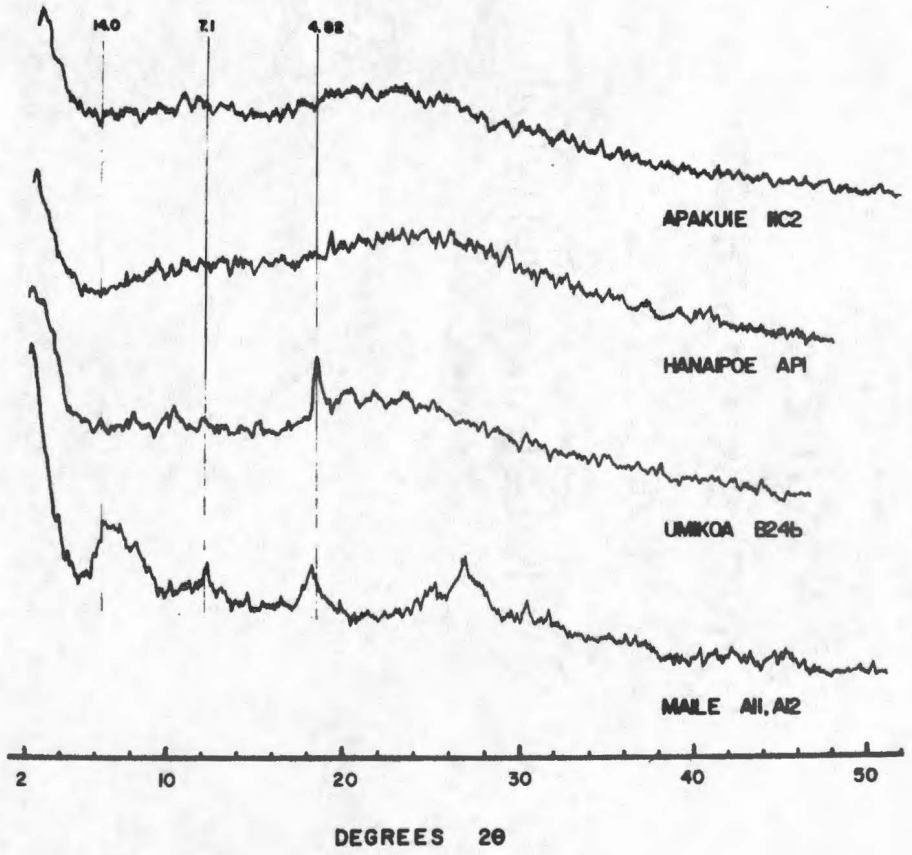


Figure 4. X-ray Diffraction Patterns of Selected Fine Clays (<0.2μ)

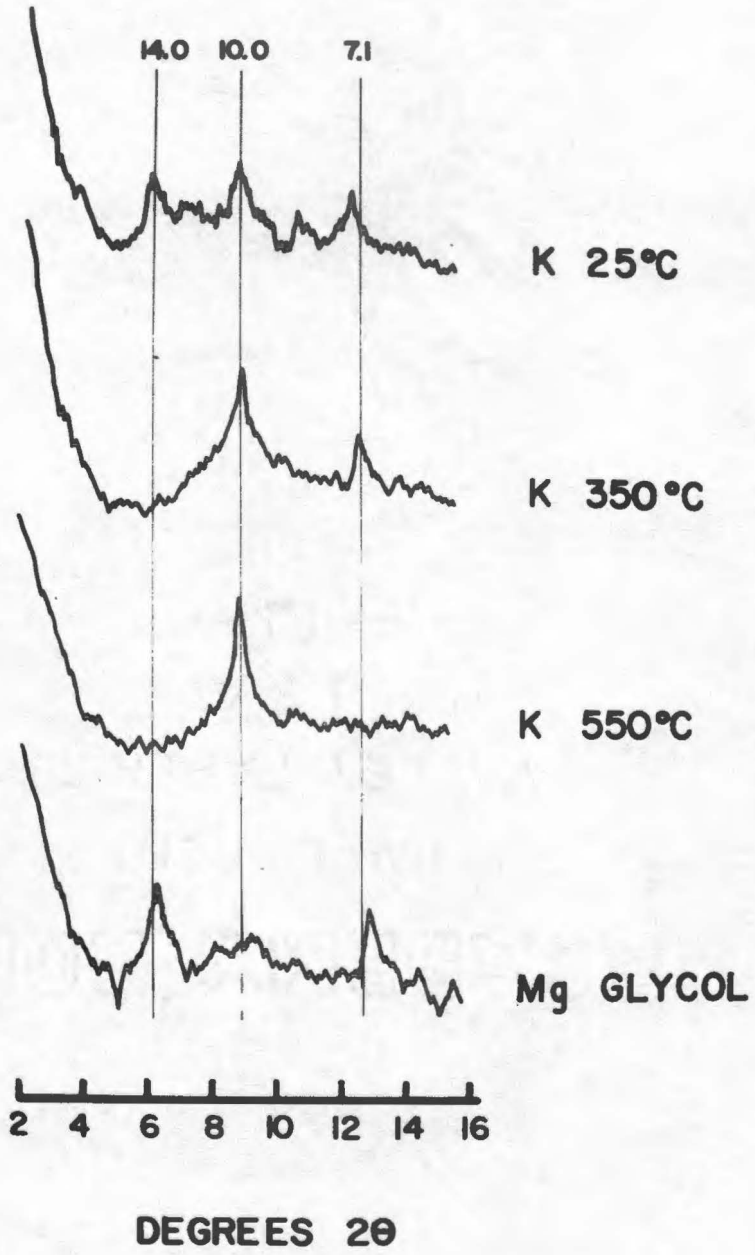


Figure 5. X-ray Diffraction Patterns of the Clay Fractions of Maile (A11, A12) Horizon After Differential Cation Saturation and Glycol Solvation

Table 2. X-ray Diffraction Analyses of Apakuie Soil

Horizons	Size Fraction	P.F.	Mg	Il	Qr	Ol	Gb	Kl(7Å)	Mc(10Å)	Vr(14Å)
A1	>50	VS	S	-	VVW	W	-	-	-	-
	2-50	VS	S	-	VVW	W	-	-	-	-
	2- 0.2	W	VW	-	-	-	-	-	-	-
B2	>50	VS	S	-	VVW	VW	-	-	-	-
	2-50	VS	S	-	VVW	VW	-	-	-	-
	2- 0.2	W	VW	-	-	-	-	-	-	-
IIAb	>50	VS	S	-	VVW	VW	-	-	-	-
	2-50	VS	S	-	VVW	VW	-	-	-	-
	2- 0.2	W	VW	-	-	-	-	-	-	-
IIC1	>50	S	S	-	VVW	VW	-	-	-	-
	2-50	S	S	-	VVW	VW	-	-	-	-
	2- 0.2	W	VW	-	-	-	-	-	-	-
IIC2	>50	S	S	-	VVW	VW	-	-	-	-
	2-50	S	S	-	VVW	VW	-	-	-	-
	2- 0.2	W	VW	-	-	-	-	-	-	-

S: Strong VW: Very weak P.F.: Plagioclase Feldspars Ol : Olivine
M: Moderate VVW: Very very weak Mg : Magnetite Gb: Gibbsite
W: Weak Il : Ilmenite Kl : Kaolinite
Qr : Quartz Mc: Mica
Vr: Vermiculite

Table 3. X-ray Diffraction Analyses of Hanaipoe Soil

Horizon	Size Fractions	P.F.	Mg	Il	Qr	Ol	Gb	Kl(7Å)	Mc(10Å)	Vr(14Å)
Ap1	>50	W	M	-	VW	-	-	-	-	-
	2-50	M	M	-	VW	VW	-	-	-	-
	2- 0.2	-	-	-	-	-	VVW	-	-	-
Ap2	>50	W	M	-	VVW	-	-	-	-	-
	2-50	M	S	-	W	VW	VVW	-	-	-
	2- 0.2	-	-	-	-	-	-	-	-	-
B21	>50	W	M	-	VVW	-	-	-	-	-
	2-50	W	M	-	W	VW	VW	-	-	-
	2- 0.2	-	-	-	-	-	-	-	-	-
B22	>50	W	M	-	VVW	-	-	-	-	-
	2-50	W	M	-	W	VW	VVW	-	-	-
	2- 0.2	-	-	-	-	-	-	-	-	-
B23	>50	W	M	-	VVW	-	-	-	-	-
	2-50	W	M	-	VW	-	VVW	-	-	-
	2- 0.2	-	-	-	-	VW	-	-	-	-
C	>50	S	M	-	-	VVW	-	-	-	-
	2-50	S	S	-	VVW	VW	VW	-	-	-
	2- 0.2	-	-	-	-	-	-	-	-	-
B24b	>50	W	M	-	VVW	-	-	-	-	-
	2-50	W	S	-	VW	VW	-	-	-	-
	2- 0.2	-	-	-	-	-	-	-	-	-

Table 4. X-ray Diffraction Analyses of Umikoa Soil

Horizon	Size Fraction	P.F.	Mg	Il	Qr	Ol	Gb	Kl(7Å)	Mc(10Å)	Vr(14Å)
Ap	>50	W	S	-	W	-	-	-	-	-
	2-50	W	S	-	M	VVW	-	-	-	-
	2- 0.2	VVW	-	-	W	-	VVW	VW	VW	VVW
B21	>50	VW	S	VW	W	-	W	-	-	-
	2-50	VW	S	W	M	VVW	VW	-	-	-
	2- 0.2	-	-	-	W	-	W	VW	VW	VW
C	>50	VW	S	VW	VW	-	VW	-	-	-
	2-50	VW	S	W	W	VVW	VW	-	-	-
	2- 0.2	-	-	-	-	-	W	-	-	-
B22b	>50	VW	S	VW	VW	-	VVW	-	-	-
	2-50	VW	S	VW	M	VVW	VW	-	-	-
	2- 0.2	-	-	-	W	-	W	VW	VVW	VVW
B23b	>50	VW	S	VW	W	-	VVW	-	-	-
	2-50	VW	S	VW	M	VVW	W	-	-	-
	2- 0.2	-	VVW	-	W	-	M	VW	VVW	VVW
B24b	>50	VW	S	VW	VW	-	VVW	-	-	-
	2-50	VW	S	W	W	VW	VVW	-	-	-
	2- 0.2	-	-	-	W	-	W	VVW	VVW	VVW

Table 5. X-ray Diffraction Analyses of Maile Soil

Horizon	Size Fraction	P.F.	Mg	Il	Qr	Ol	Gb	Kl	Illite	Vr
A11, A12	>50	-	W	VVW	W	VW	-	-	-	-
	2-50	-	M	VW	VS	VW	-	-	-	-
	2- 0.2	-	-	-	M	-	VVW	VW	W	W
A13	>50	-	W	VVW	W	-	-	-	-	-
	2-50	-	M	VW	M	VW	-	-	-	-
	2- 0.2	-	-	-	W	-	W	W	W	VW
IB21, IIB22,	>50	-	M	VVW	W	VW	-	-	-	-
IVB23, VC	2-50	-	W	VW	M	VW	VW	-	-	-
	2- 0.2	-	-	-	VW	-	VW	W	VW	VVW
VIB24	>50	-	M	VVW	W	VW	-	-	-	-
	2-50	-	M	VW	VS	VW	VW	-	-	-
	2- 0.2	-	-	-	M	-	W	M	W	VVW
VIIB25	>50	-	M	VVW	W	VVW	-	-	-	-
	2-50	-	S	VW	W	VW	VW	-	-	-
	2- 0.2	-	-	-	VW	-	W	W	VW	VVW
VIIB26	>50	-	M	VVW	VW	VVW	-	-	-	-
	2-50	-	S	VW	W	VW	VW	-	-	-
	2- 0.2	-	-	-	W	-	VW	W	W	VVW

Table 6. X-ray Diffraction of Selected Fine Clay (<0.2μ) Fractions

Soils	Horizons	P.F.	Mg	Il	Qr	Ol	Gb	Kl(7Å)	Mc(10Å)	Vr(14Å)
Apakuie	A1	W	-	-	-	-	-	-	-	-
	IIAb	VW	-	-	-	-	VVW	-	-	-
	IIC2	VW	-	-	-	-	-	-	-	-
Hanaipoe	Ap1	VVW	-	-	-	-	-	-	-	-
	B22	-	-	-	-	-	-	-	-	-
	B24b	VVW	-	-	-	-	-	-	-	-
Umikoa	B21	-	-	-	-	-	VVW	VW	VVW	-
	B24b	-	-	-	-	-	M	VW	VVW	VVW
Maile	A11, A12	-	-	-	W	-	VW	W	W	M
	IIB21, IIIB22, IVB23, VC	-	-	-	VW	-	W	VW	-	-

Feldspars were found to be abundant in the weakly weathered Apakuie sand and silt (Figure 2). According to Goodyear and Duffin (1954), plagioclase feldspars can be distinguished from alkali feldspars by:

1. Two very strong reflections in the region 3.17 - 3.22 Å
2. A medium reflection of spacing 6.4 to 6.5 Å
3. Three medium to strong reflections with spacings 4.03 - 4.05, 3.74 - 3.78, 3.61 - 3.67 Å

All these characters were found in Apakuie and some horizons of the other soils, and, hence, it was concluded that the feldspars found in these soils are of the plagioclase type. From the intensity of the peaks shown in Tables 2-6 the amount of feldspars in the coarse fraction decreases in the sequence Apakuie > Hanaipoe > Umikoa > Maile showing that the degree of weathering of these soils increases in this order. The relative abundance of this mineral in some of the horizons of these soils shows the relative degree of weathering within profiles. The above statements about the degree of weathering are always not true since the mineralogical composition of the parent material is variable to a degree.

The identification of quartz in Hawaiian soils and the inability to detect this mineral in the parent rock suggests that this is formed as a secondary mineral. Many workers have tried to explain this by different theories but none was found to be completely acceptable. These different theories are discussed in a

later section of the thesis. Most of the workers have found that quartz content increases with rainfall and decreases from the surface horizon downwards. A similar trend was found in the sequence under study. Quartz was found to increase in the rainfall sequence: Apakuie < Hanaipoe < Umikoa < Maile. The relationship of quartz with horizon and rainfall is shown in the Figure 6. The percentage of quartz was calculated from the standard curve prepared by Gardiner (1967). The amount of quartz is generally found to be highest in the surface horizon, then decreases up to the middle of the profile and then increases and finally decrease indicating the presence of buried horizons.

The minerals present in the clay fractions are also shown in Tables 2-6 and Figures 3-5. The relative abundance of some of the weakly formed minerals was difficult to determine due to the background scattering of the amorphous colloids. Small amounts of secondary minerals were found, mainly in Umikoa and Maile. Gibbsite was found to be greatest in Umikoa and Maile and least in Hanaipoe and Apakuie.

The presence of weak 14 Å, 10 Å and 7.0 Å diffraction maxima suggested the presence of some layer lattice type minerals.

The layer silicates were found to increase in the order: Apakuie < Hanaipoe < Umikoa < Maile. The results of differential cation saturation and glycol solvation of some of the clays are shown in Figures 3-5. The 10 Å d-spacing persists and is

Table 7. Allophane and Quartz Content of the Soils

Apakuie

Horizon	% Quartz*	Area under DTA peak in sq. inches	% Allophane**
A1	1.81	0.44	29.3
B2	1.31	0.51	34.0
IIAb	1.25	0.50	33.3
IIC1	0.98	0.47	31.3
IIC2	0.71	0.40	27.0

Umikoa

Horizon	% Quartz*	Area under DTA peak in sq. inches	% Allophane**
Ap	5.26	0.80	53.3
B21	6.40	1.29	86.0
C	2.66	1.32	88.0
B22b	3.68	1.18	78.7
B23b	3.98	1.15	76.7
B24b	1.42	1.23	82.0

Table 7. Allophane and Quartz Content of the Soils (Continued)

Hanaipoe

Horizon	% Quartz*	Area under DTA peak in sq. inches	% Allophane**
Ap1	1.88	0.72	48.0
Ap2	2.00	1.16	77.3
B21	2.45	1.01	67.3
B22	2.28	1.23	82.0
B23	1.60	1.20	80.0
C	0.82	1.06	70.7
B24b	1.12	1.01	67.3

Maile

Horizon	% Quartz	Area under DTA peak in sq. inches	% Allophane**
A11, A12	6.87	0.40	26.7
A13	3.77	0.60	40.0
IIB21, IIIB22, IVB23, VC	3.47	0.79	52.7
VIB24	5.70	0.57	38.0
VIIB25	3.25	0.64	42.7
VIIIB26	4.02	0.71	47.3

* Percentage on the basis of deferrated, organic matter free soil.

** Percentage is calculated on the basis that Apakuie IIC2(<0.2μ) is 100% allophane; small amounts of free alumina and silica are also included.

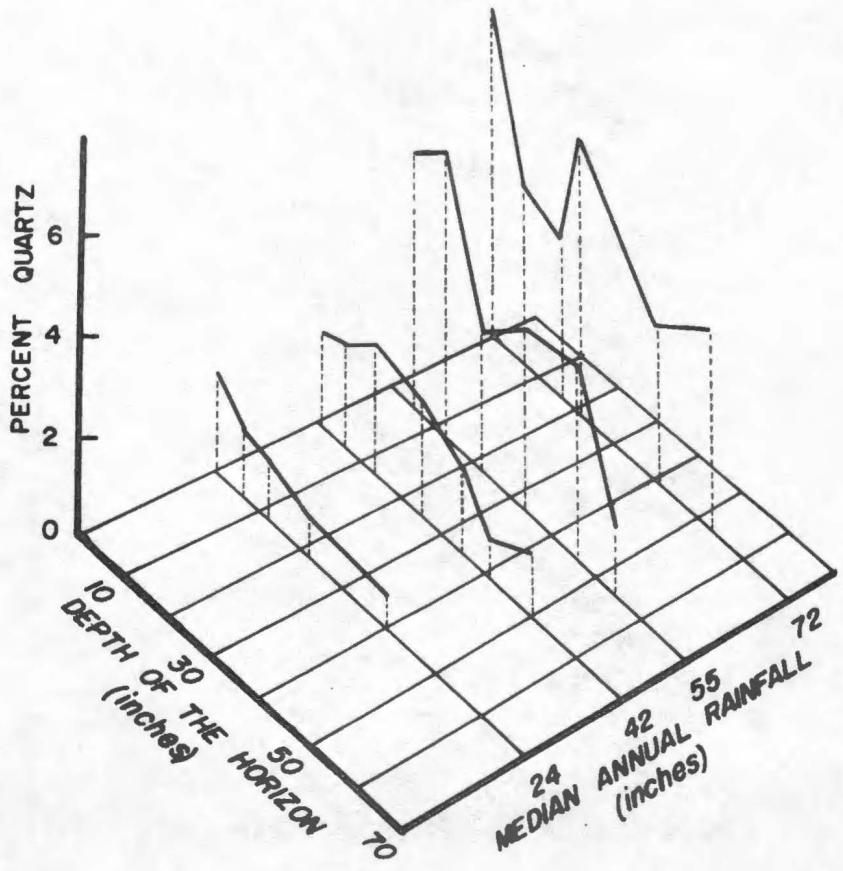


Figure 6. Quartz Content of the Soils as a Function of Rainfall and Depth of the Horizon

sometimes enhanced throughout the Mg-saturation and K-saturation treatment. It is therefore considered to be due to a mica. The 14 Å d-spacing was found to have no expansion on Mg-saturation and glycol solvation and collapsed to 10 Å on K-saturation and heating to 350°C. It is therefore considered to be due to vermiculite. Observations on the diffraction patterns indicated that the 7 Å is due to kaolin and not due to chlorite or vermiculite. No peak or band was found in the 4.4 Å region, and, therefore, it was not possible to distinguish between kaolinite and halloysite from the weakly formed 7 Å peak.

The fine clay fraction (<0.2μ) was found to be very different from the coarse clay fraction (2μ - 0.2μ). A high level of background scattering in X-ray diffraction was found to occur in the region of 3.7 Å. This scattering was interpreted as due to allophane. There are also indications of the presence of gibbsite, weakly formed layer silicates and some primary minerals such as feldspar and quartz. Feldspars were found mainly in Apakuie; layer silicates, quartz and gibbsite in Umikoa and Maile.

The results of X-ray diffraction of the sand and silt fractions indicate that the degree of weathering increases in the order Apakuie < Hanaipoe < Umikoa < Maile, and of the clay fraction indicate that the degree of crystallinity of the clay increases in the order Apakuie < Hanaipoe < Umikoa < Maile.

Differential Thermal Analyses

D.T.A. patterns of selected fine and coarse clays are shown in Figures 8-9. All these clays showed a single broad endothermic peak between 100°C and 200°C with maxima between 120°C to 150°C and a sharp exothermic peak in the region of 850°C to 950°C. Since the layer silicates are either absent or present in very small amounts the endothermic peaks are considered to be due to the water of hydration of allophane and the exothermic peaks are due to phase changes of allophane. Similar results were reported on allophane examined by Fieldes (1955), Aomine (1962), Egawa (1964), Birrel and Fieldes (1952).

Endothermic peaks at 295°C due to gibbsite were obtained in most of these clays examined. This peak was found to be intense in the case of Maile and Umikoa and very weak in Apakuie and Hanaipoe. In Maile and Umikoa clays, surface horizons do not have much gibbsite as compared with other horizons. Similar results were observed in the X-ray diffraction studies.

Marked exothermic reactions between 400°C and 700°C, as reported by Fieldes (1955) on New Zealand soils derived from volcanic ash, are due to characteristic burning off of organic matter which has been retained by the clay in spite of prolonged H_2O_2 treatment. A broad, sometimes continuous, exothermic peak is also observed in the clays in the present study. It is clearly evident in the first two surface horizons of Maile coarse

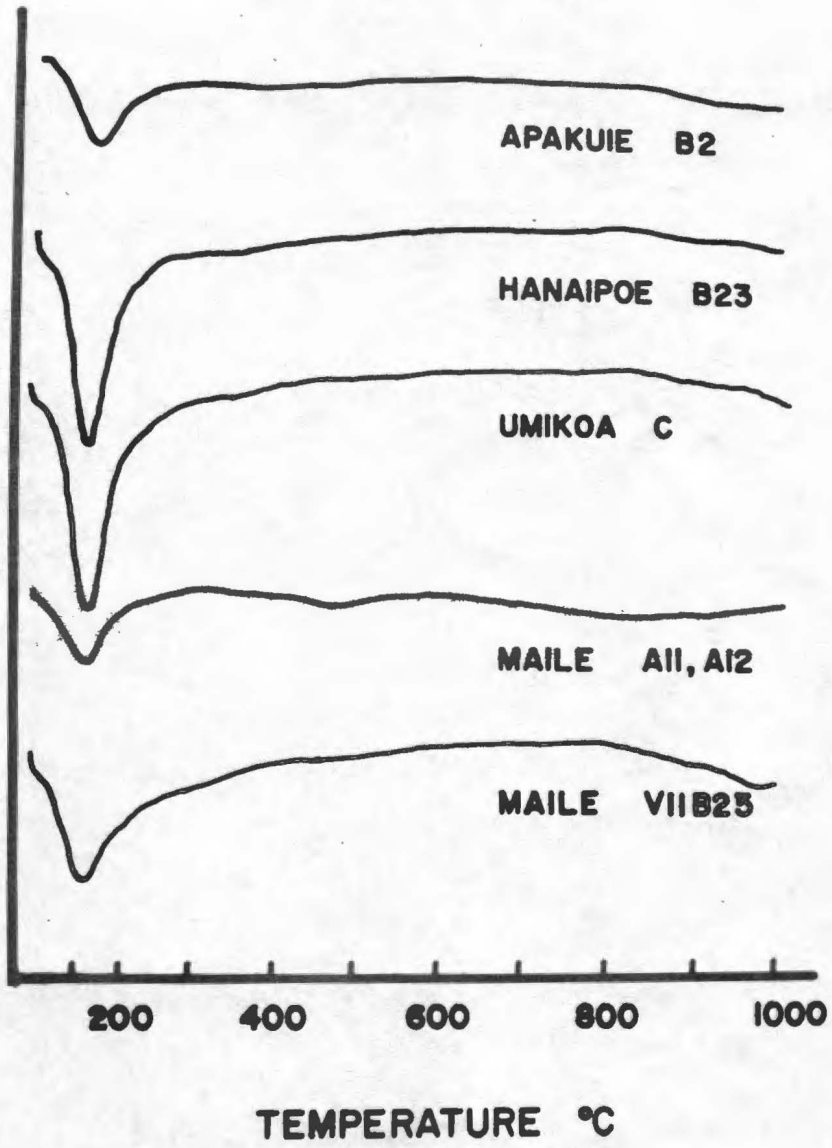


Figure 7. Differential Thermal Analyses Patterns of Selected Soils

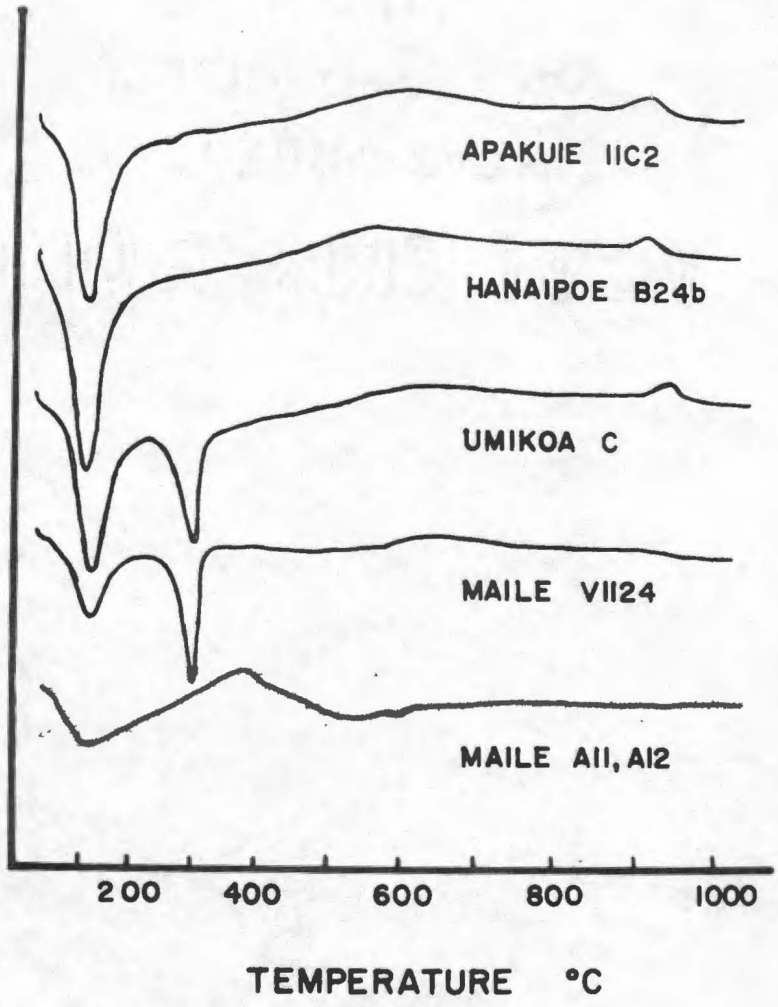


Figure 8. Differential Thermal Analyses Patterns of Selected Coarse Clays (2μ - 0.2μ)

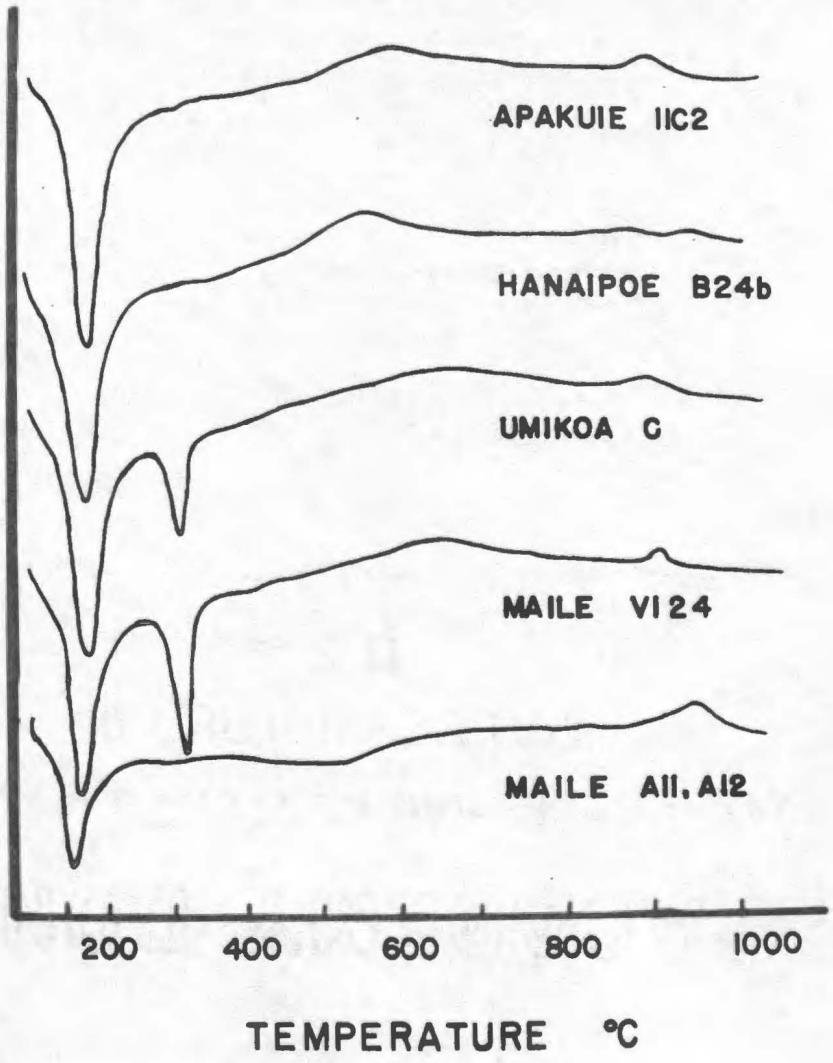


Figure 9. Differential Thermal Analyses Patterns of Selected Fine Clays (2μ - 0.2μ)

clays.

Tiny endothermic peaks due to layer silicates in the region of 450°C to 600°C were also observed in the surface horizons of Maile clays. The exact type of layer silicate cannot be determined.

The fine clay fractions have more intense first endothermic peaks than the coarse clays, and, hence, contain more allophane than the coarse clays. The areas of the first endothermic peaks which correspond to the amount of allophane was measured and presented in Table 8. From the areas of the peaks of these clay fractions, it is apparent that the amount of allophane in the clay fraction increases in the order: Maile < Umikoa < Hanaipoe < Apakuie. The areas of the first endothermic peaks of the whole soils were also measured and presented in Table 7. This is an indication of the amount of amorphous material in the whole soil which depends on the amount and type of clay, amount of glass in the coarse fractions and on some other factors. From these areas determined, the amount of amorphous material in the whole soil is found to increase in the order: Apakuie < Maile < Hanaipoe < Umikoa.

The percentages of allophane in the whole soil and clays were estimated on the basis that Apakuie (30 - 50"; <0.2μ), which has the highest peak area, is 100 percent allophane, and on the assumption that very little or no layer silicates were present in all the samples. The last assumption is made since layer

Table 8. Percentage of Allophane in Selected Clays

Soil	Horizon	Clay Fraction in μ	Area under the peak in sq. inches	% Allophane*
Apakuie	B2	2-0.2	1.03	68.7
	IIC2	2-0.2	1.18	78.7
		<0.2	1.50	100.0
Hanaipoe	Ap1	2-0.2	0.89	59.3
	B24b	2-0.2	1.30	86.7
		<0.2	1.30	86.7
Umikoa	C	2-0.2	1.13	75.3
		<0.2	1.34	89.3
	B23b	2-0.2	0.69	46.0
Maile	A11, A12	2-0.2	0.29	19.3
		<0.2	0.84	56.0
	IIB21, IIIB22, IVB23, VC	2-0.2	1.09	72.7
		<0.2	1.44	96.0
	VIB24	2-0.2	0.50	33.3
		<0.2	1.17	78.0
Choyo	30" - 75"	2-0.1	1.11	74.0

*Percentage is calculated on the basis that Apakuie IIC2 (<0.2μ) is 100% allophane.

silicates such as montmorillonite, vermiculite and halloysite also give endothermic peaks in the region of 150°C. Lai (1967) on studying amorphous soils from Japan and Hawaii found that Choyo (1μ - 0.2μ) was the most allophanic of those he studied. In the present study many clays were found to contain more allophane than Choyo clay, which was found to contain only 74 percent allophane on the basis of the new standard.

Soil pH

Soil pH was determined both in H_2O and KCl (Table 9). The pH in water was higher than the pH in KCl in all the soils. The pH is found to be low at the surface and generally increases down the profile. Although these soils are found to have high exchange acidity as indicated by the exchange $[H^+]$, pH values are comparatively high due to the fact that allophane or the amorphous polymerized alumina gels have high buffering capacity in the region of their isoelectric points.

Mean pH values of the whole profile were found to be negatively correlated with rainfall as shown by the regression line in Figure 10. This is due mainly to the increase in leaching of bases and silica followed by enrichment of alumina which dissolves at this low pH and produces more hydrogen ions.

The ΔpH was found to increase with increasing rainfall as shown in Figure 11. This is caused by the increase of pH_{KCl} with

Table 9. pH Values and Exch. $[H^+]$ of the Whole Soils

Horizon	pH H_2O	pH KCl	ΔpH (H_2O-KCl)	Exch. $[H^+]$ *
Apakuie				
A1	5.82	5.40	0.42	16.9
B2	6.45	5.50	0.95	28.8
IIAb	6.70	5.65	1.05	25.92
IIC1	6.82	5.78	1.04	19.20
IIC2	6.95	5.75	1.20	9.88
Mean**	6.65		1.21	
Hanaipoe				
Ap1	5.10	4.60	0.50	38.28
Ap2	6.00	5.25	0.75	61.04
B21	6.20	5.21	0.99	67.65
B22	5.95	4.98	0.97	80.62
B23	6.00	5.05	0.95	76.55
C	6.45	5.38	1.07	50.47
B24b	6.18	5.20	0.98	79.43
Mean**	5.95		0.90	

Horizon	pH H_2O	pH KCl	ΔpH (H_2O-KCl)	Exch. $[H^+]$ *
Umikoa				
Ap	5.85	4.83	1.02	63.43
B21	5.95	5.05	0.90	85.48
C	5.98	5.13	0.85	88.55
B22b	5.90	5.10	0.80	89.41
B23b	5.80	5.12	0.68	93.92
B24	5.65	5.15	0.50	76.99
Mean**	5.76		0.71	
Maile				
A11, A12	4.68	4.38	0.30	29.93
A13	5.32	4.93	0.39	65.29
IIB21, IIB22, IVB23, VC	5.50	5.27	0.23	39.12
VIB24	5.55	5.32	0.23	51.85
VIIB25	5.50	5.13	0.37	74.13
VIIIB26	5.92	5.50	0.42	35.21
Mean**	5.40		0.30	

* Exch. $[H^+]$ = C.E.C. - $\sum$ exch. Bases.
**Mean of all horizons except the last were taken.

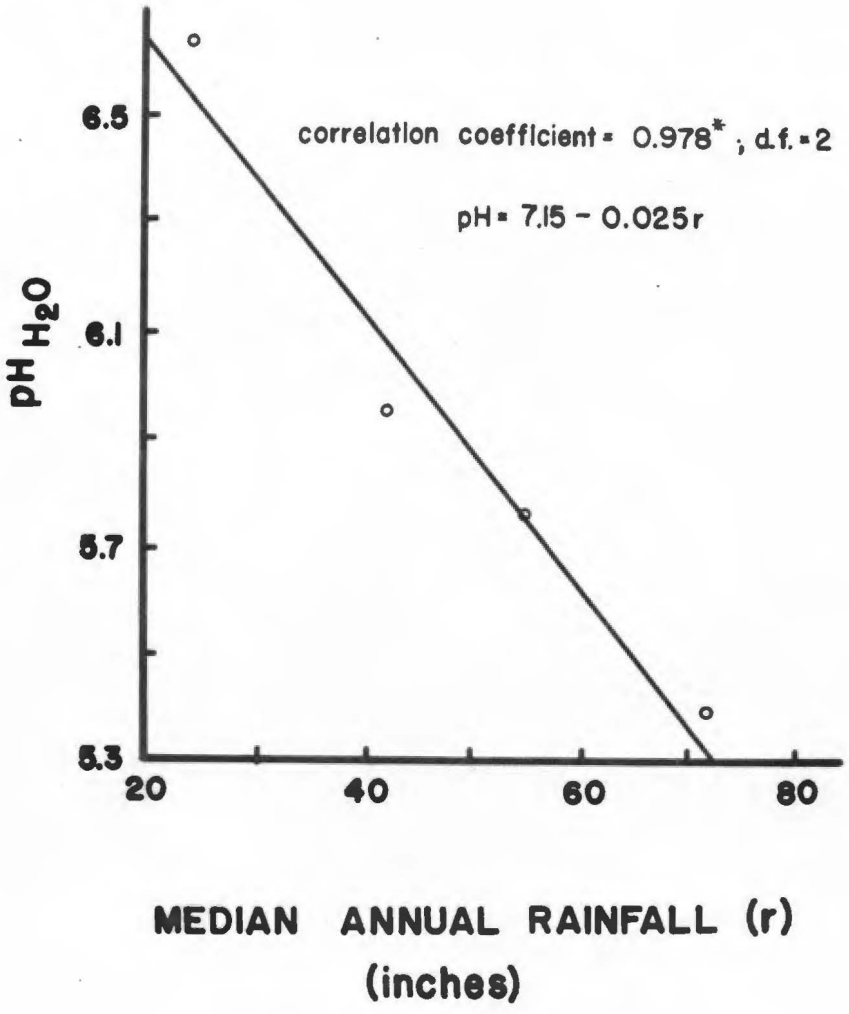


Figure 10. Variation of pH with Rainfall

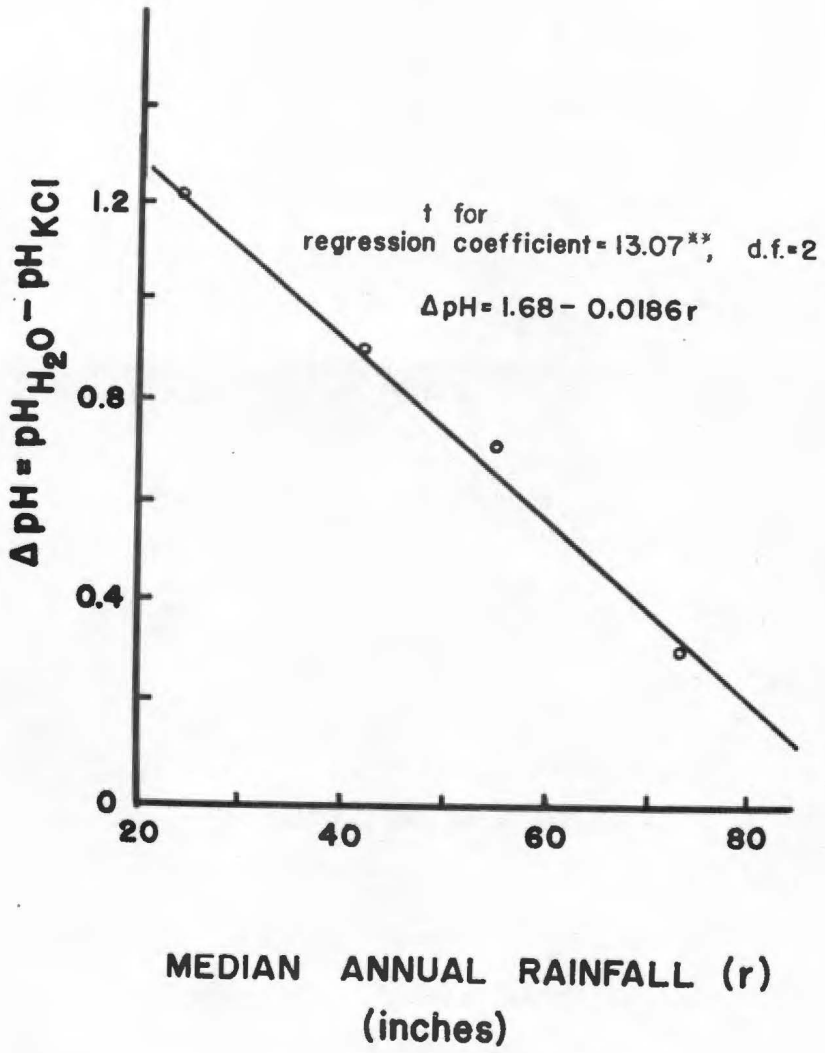


Figure 11. Variation of ΔpH with Rainfall

increase in rainfall. It is suggested that the increase of pH_{KCl} is due to the following fact: The replacement of OH^- by Cl^- proceeds at a faster rate than the replacement of H^+ by K^+ as the amount of rainfall increases in the sequence, i.e. the net negative charge in the exchange complex decreases with increasing rainfall. This can be explained by the following reasoning: the soils under discussion have high amounts of amorphous colloids whose charges are highly pH dependent. Hence, net negative charge decreases with decreasing pH. In this sequence of soils, as the rainfall increases, pH_{H_2O} decreases, and, therefore, the net negative charge decreases. It should be noted that the net negative charge at the field condition cannot be considered to be equivalent to the total negative charge as measured by cation exchange capacity in the laboratory at pH 7.

Carbon, Nitrogen and Carbon-Nitrogen Ratio

Organic carbon contents range from 2 percent to 21 percent with an average of about 11 percent. Carbon-nitrogen ratios range from 10 to 24, with an average of about 17. Similar values were obtained for volcanic ash soils of Japan (Kanno, 1952). The surface horizons of all soils have high carbon content that decreases down the profiles. An increase of organic carbon in a few lower horizons is probably due to the presence of buried horizons.

Table 10. Carbon, Nitrogen, and Carbon-Nitrogen Ratios of the Whole Soils

Apakuie			
Horizon	C	N	C/N
A1	16.50	1.102	14.97
B2	6.10	0.580	10.52
IIAb	5.52	0.432	12.78
IIC1	3.30	0.238	13.86
IIC2	1.98	0.134	14.78
Mean*	5.26	0.410	13.01

Umikoa			
Horizon	C	N	C/N
Ap	14.00	1.062	13.18
B21	11.28	0.623	18.11
C	9.71	0.539	18.01
B22b	9.18	0.466	19.70
B23b	9.15	0.545	16.79
B24b	5.94	0.445	13.35
Mean*	10.52	0.642	17.36

Hanaipoe			
Horizon	C	N	C/N
Ap1	21.31	1.579	13.50
Ap2	15.09	1.039	14.52
B21	11.61	0.730	15.90
B22	9.36	0.666	14.05
B23	8.71	0.594	14.66
C	4.64	0.241	19.25
B24b	6.19	0.489	12.66
Mean*	11.25	0.776	14.46

Maile			
Horizon	C	N	C/N
A11, A12	11.05	0.636	17.37
A13	11.51	0.685	16.80
IIB21, IIB22, IVB23, VC	9.56	0.560	17.07
VIB24	9.00	0.440	20.45
VIIB25	9.20	0.428	21.50
VIIIB26	5.08	0.208	24.42
Mean*	9.92	0.541	18.64

*The mean of all horizons except the last was calculated for every soil.

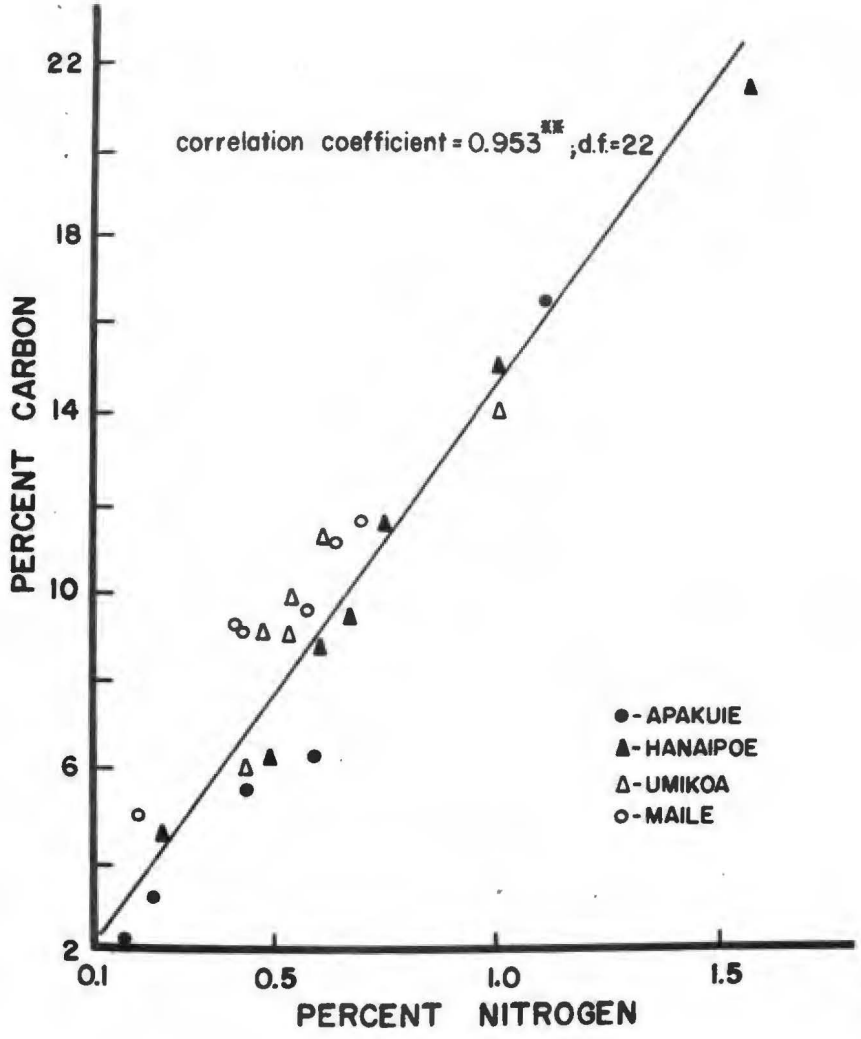


Figure 12. Relation Between Carbon and Nitrogen Content of the Soils.

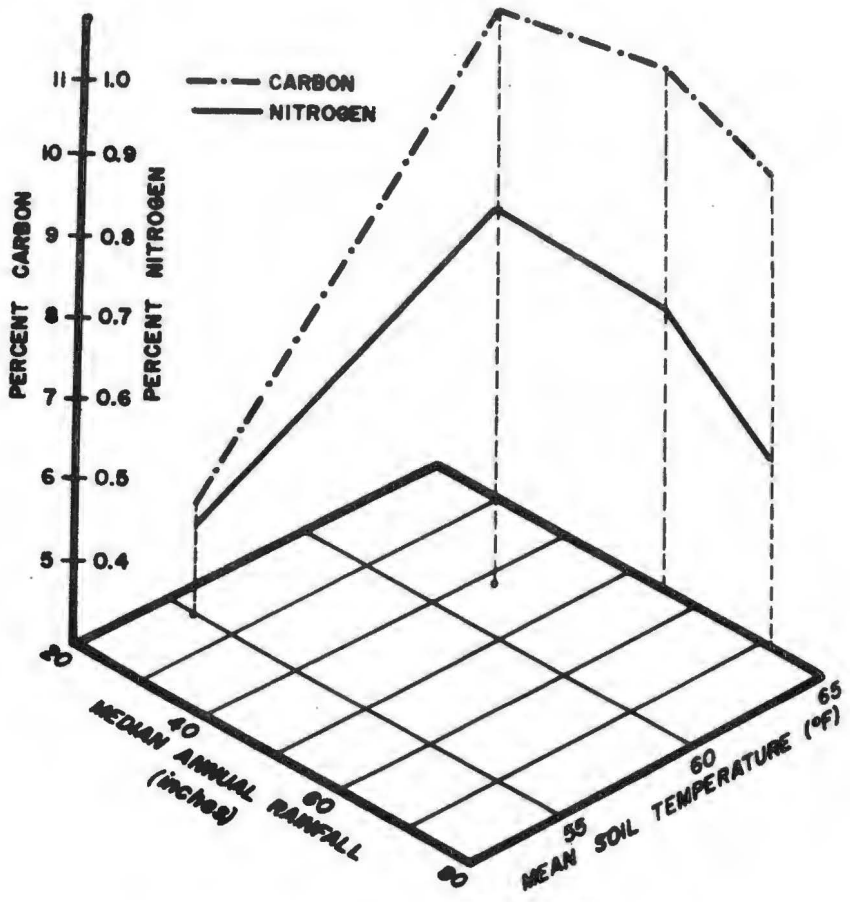


Figure 13. Variations of Carbon and Nitrogen with Rainfall and Temperature

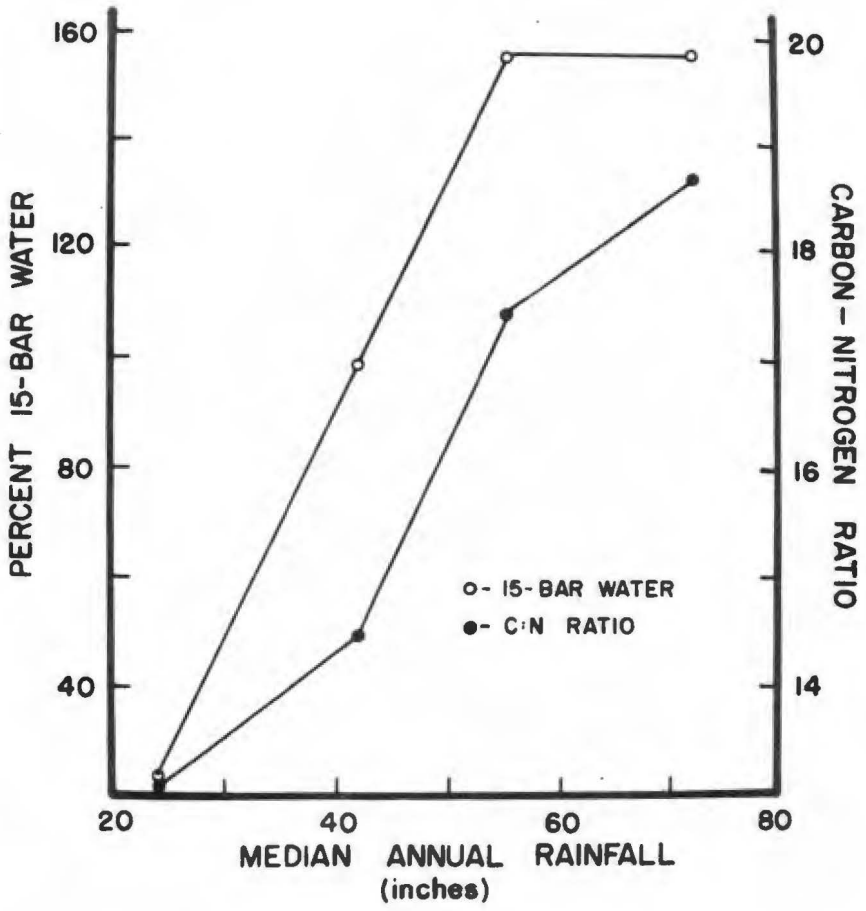


Figure 14. Variations of 15-Bar Water and Carbon-Nitrogen Ratio with Rainfall

The high organic matter content of volcanic ash soils is considered to be due to the high water holding capacity of these soils which inhibits the decomposition of organic matter (Kawamura, 1952). The slow decomposition of organic matter may also be due to the formation of resistant Fe, Al humus complexes.

Carbon was found to be highly correlated with nitrogen as normally expected (Figure 12).

Since carbon and nitrogen depend on both temperature and rainfall, a 3-dimensional graph is presented to show the effect of these environmental factors on these soil properties (Figure 13). As a general rule, carbon and nitrogen increase with increasing rainfall and decrease with increasing temperature, that is, the effects of temperature and rainfall are opposite to each other. This is true in the sequence under study, carbon and nitrogen increase from Apakuie to Hanaipoe and then decrease to Umikoa and Maile. Carbon-nitrogen ratio is found to increase linearly with increase in rainfall in the sequence (Figure 14).

Free Iron Oxides

Free iron oxide was determined in the whole soil and then calculated on the basis of the amount present in the inorganic fraction of the soil (Table 11). Minerals present in the free iron oxides are probably Haematite and Geothite. These are the main minerals extracted by dithionite treatment although some of the other

Table 11. Amount of Free Iron Oxides in 100 gm of Mineral Soil

Apakuie	
Horizons	Free iron oxides in gms
A1	10.40
B2	13.10
Ab	10.43
IIC1	8.95
IIC2	6.71
Mean	10.22

Umikoa	
Horizons	Free iron oxides in gms
A1	21.09
B21	15.79
C	12.11
B22b	12.78
B23b	17.24
B24b	11.99
Mean	15.47

Hanaipoe	
Horizons	Free iron oxides in gms
Ap1	15.68
Ap2	17.25
B21	15.95
B22	18.13
B23	13.84
C	7.65
B24b	14.24
Mean	15.52

Maile	
Horizons	Free iron oxides in gms
A11, A12	37.50
A13	14.47
IIB21, IIIB22, IVB23, VC	14.89
VIB24	17.42
VIIB25	10.93
VIIIB26	8.87
Mean	16.06

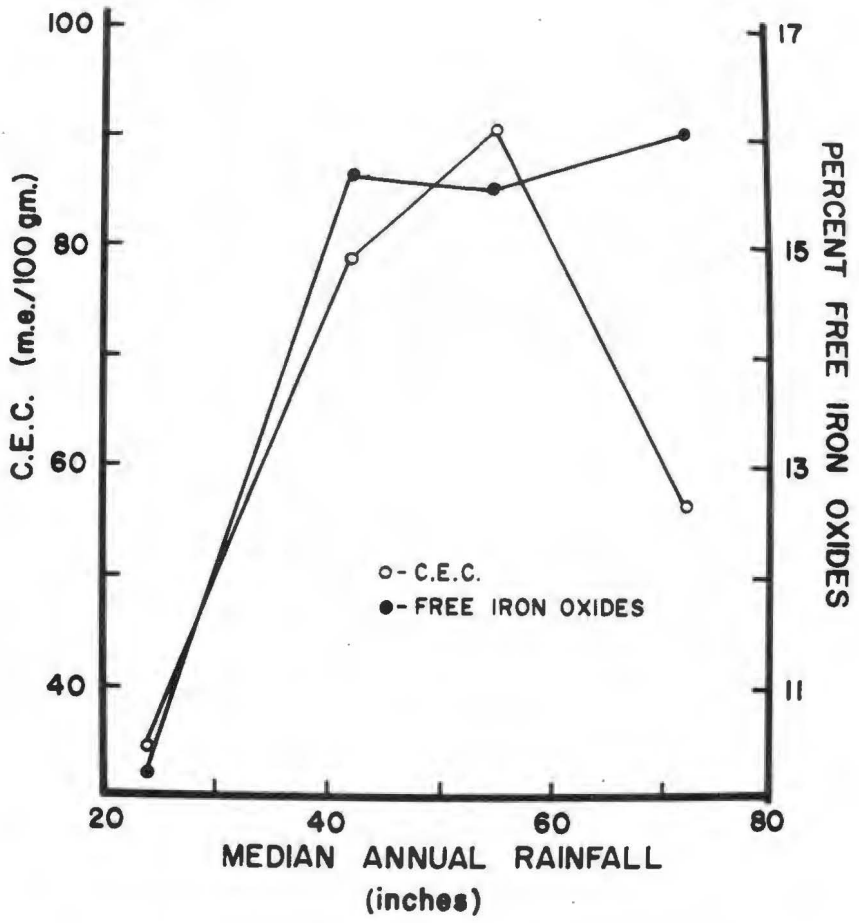


Figure 15. Variations of Cation Exchange Capacity and Free Iron Oxides with Rainfall

resistant iron minerals are also slightly attacked. Free iron oxides in the mineral soils range from 6.7 to 37.5 with greatest amounts in the surface horizon of Maile.

Amount of free iron oxides in these soils gives an indication of the relative weathering of these soils assuming there is constant amount of total iron. In the sequence under study, free iron oxide increases with increasing temperature and rainfall, as shown in Figure 15. Within the profiles, free iron oxides are generally found to be higher in the surface horizons and lower in the deep horizons. Some abrupt changes occur in some places of the profile due to buried horizons. The accumulation of free iron oxides in the surface horizons of the higher rainfall soils (Umikoa, Maile) is expected since an alternate wet and dry condition exists in the surface of these soils.

It is also interesting to note that the C horizons of all these soils have very low values of free iron oxides compared to the adjacent horizons in the same profiles.

Cation Exchange Capacity and Base Saturation

Cation exchange capacity of these soils ranges from 15 to 97 m.eq/100 gms as shown in Table 12. Cation exchange capacity increases from Apakuie to Umikoa and then decreases to Maile (Figure 15). This variation is due to the relative amounts of organic matter and clay and the type of clay. Since the

Table 12. Cation Exchange Capacities of the Whole Soil

Apakuie

Horizon	C.E.C. at pH 7	Ca	Mg	K	Na	B.S.%
A1	40.8	19.40	3.52	0.92	0.061	58.58
B2	41.9	10.85	1.60	0.58	0.074	31.26
Ab	38.5	10.70	1.40	0.42	0.060	32.68
IIC1	29.6	8.53	1.35	0.45	0.070	35.14
IIC2	15.0	3.81	0.62	0.62	0.072	34.13
Mean*	34.87					35.34

Umikoa

Horizon	C.E.C. at pH 7	Ca	Mg	K	Na	B.S.%
Ap	72.1	6.21	2.0	0.37	0.091	12.02
B21	94.9	7.54	1.6	0.14	0.142	9.93
C	94.7	4.96	1.05	0.11	0.036	6.49
B22b	93.0	3.11	0.28	0.09	0.114	3.86
B23b	97.0	2.00	0.50	0.17	0.315	3.08
B24b	79.1	1.23	0.95	0.16	0.115	3.11
Mean*	90.21					6.73

*Mean of all horizons except the last.

Table 12. Cation Exchange Capacities of the Whole Soil (Continued)

Hanaipoe

Horizon	C.E.C. at pH 7	Ca	Mg	K	Na	B.S.%
Ap1	56.5	10.4	7.3	0.46	0.059	32.19
Ap2	85.9	20.0	4.53	0.25	0.077	28.94
B21	85.8	13.6	4.13	0.20	0.219	21.15
B22	88.0	5.37	1.81	0.01	0.191	8.39
B23	81.4	2.77	1.81	0.09	0.182	5.96
C	52.6	1.21	0.77	0.09	0.062	4.05
B24b	81.8	2.03	0.18	0.03	0.128	2.90
Mean*	78.54					15.00

Maile

Horizon	C.E.C. at pH 7	Ca	Mg	K	Na	B.S.%
A11, A12	37.1	1.96	0.38	0.23	0.091	7.17
A13	66.6	0.48	0.20	0.12	0.073	1.31
IIB21, IIIB22, IVB23, VC	40.9	0.42	0.18	0.08	0.048	1.78
VIB24	53.6	0.44	0.34	0.09	0.066	1.75
VIIB25	75.4	0.57	0.30	0.06	0.029	1.27
VIIIB26	37.5	0.50	0.22	0.09	0.051	2.29
Mean*	56.21					2.00

*Mean of all horizons except the last.

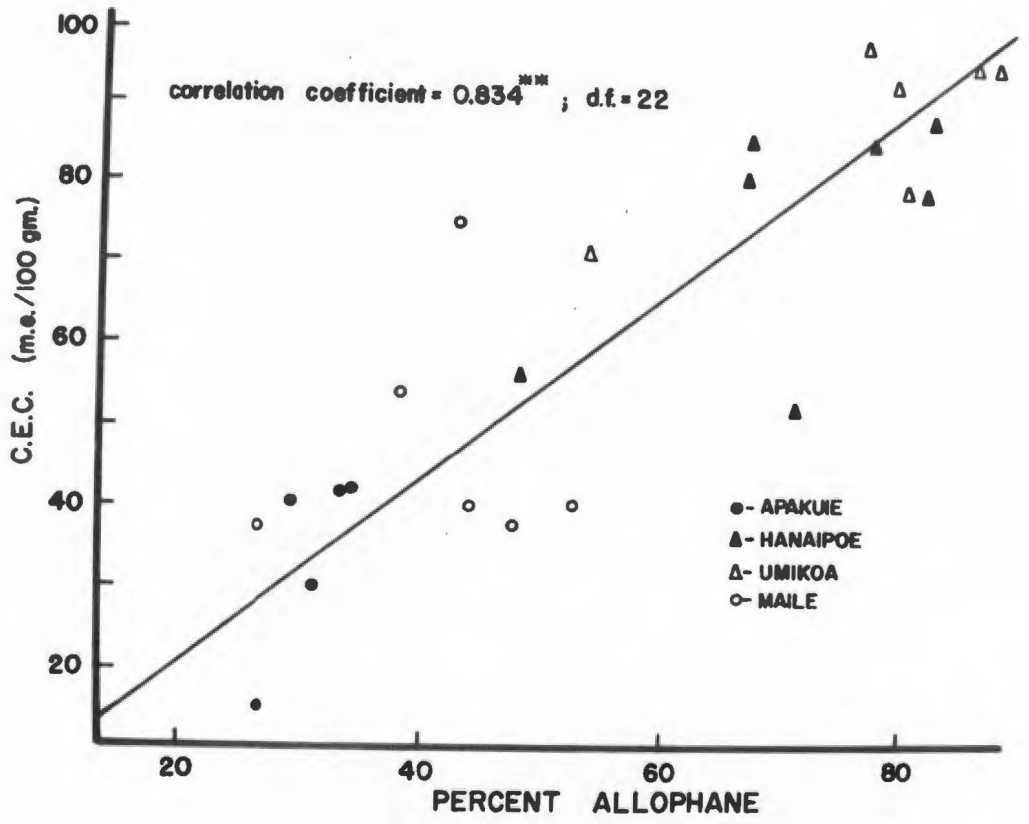


Figure 16. Correlation Between Cation Exchange Capacity and Percent Allophane

layer silicates are in small amounts the cation exchange capacity of these soils is due mainly to the type and amount of amorphous colloids. A highly significant correlation between cation exchange capacity and area under the first endothermic peak in D.T.A. (which represents the amount of amorphous colloids) was found (Figure 16). According to the peak areas, the amount of amorphous material increases in the order Apakuie < Maile < Hanaipoe < Umikoa, and the cation exchange capacity follows the same order.

Another explanation for this variation of cation exchange capacity is also possible. The cation exchange capacity of allophane is due mainly to the negative charges created by the dissociation of the H from the silanol groups and in part due to the negative charge arising from isomorphous substitution of aluminum for silicon in the tetrahedran. Many workers have found that the four coordinated aluminum increases up to a certain $\frac{Al_2O_3}{Al_2O_3+SiO_2}$ weight ratio (20 to 30 percent), and a shift of this coordination number from four to six takes place with further increase of this ratio (Millikan et al., 1950; DeKimpe et al., 1961). In the sequence under study, as the rainfall increases, leaching of silica increases, and, hence, the weight ratio $\frac{Al_2O_3}{SiO_2+Al_2O_3}$ increases. Thus, it may be possible that a shift of coordination number takes place at Umikoa, and the cation exchange

capacity decreases in this sequence. Decrease of cation exchange capacity from Umikoa to Maile is, in addition, due to the dilution of the clay by inactive free iron oxide which is present in high amounts in Maile.

Exchangeable bases and percent base saturation are presented in Table 12. The relative abundance of the exchangeable bases decreases in the order: Ca > Mg > K > Na. Exchangeable Ca and Mg are found to decrease to a great degree with increasing rainfall. Two interesting points should be considered to explain this fact. The soils derived from volcanic ash have high capacity to adsorb cations due to their high net negative charge. But the power to hold the ions will be low if the degree of leaching is high and the soils are very permeable. Base saturation varies logarithmically with rainfall as shown in the Figure 17. This is to be expected from the fundamental principle of thermodynamics that energy is related logarithmically to concentration. Here energy is considered to be the leaching effect of the rainfall which is a measure of the bond energy between positively charged ions and negatively charged clay. The concentration is measured by the base saturation.

Very low base saturation with high cation exchange capacity of the soils in the higher rainfall area (e.g. Maile) is due to the large amount of exchangeable $[H^+]$ or hydroxy aluminum ions (Table 9). The pH values of the higher rainfall soils are as low

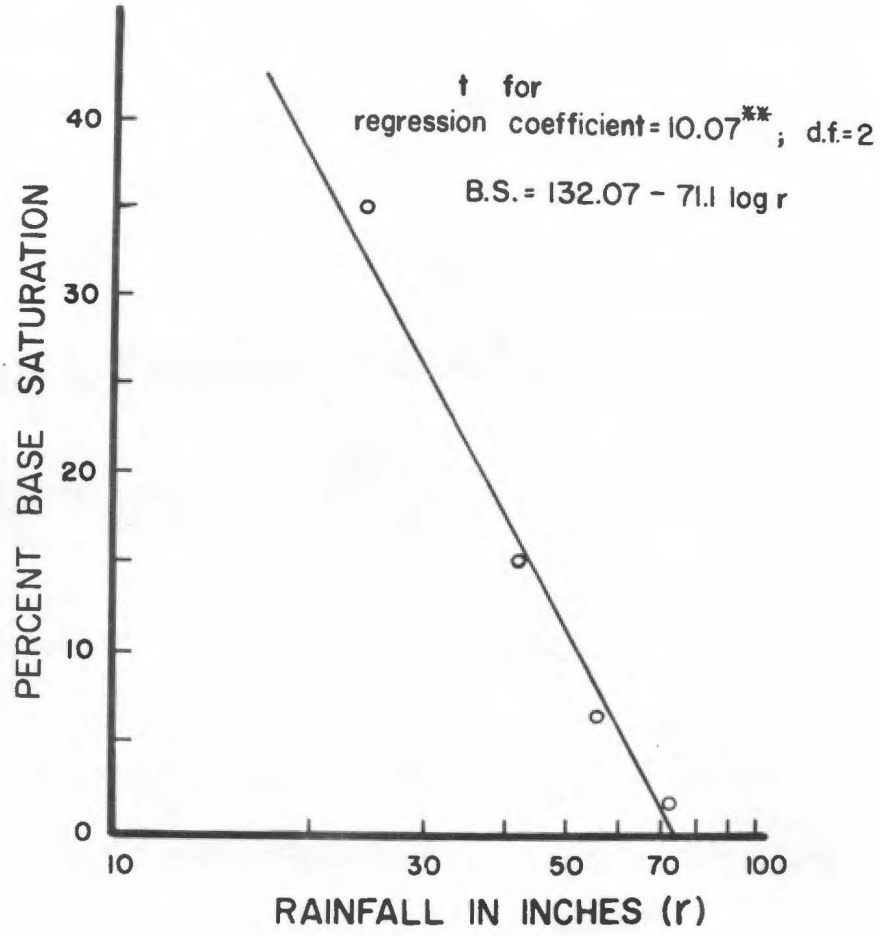


Figure 17. Variation of Base Saturation with Median Annual Rainfall in Semi-Logarithmic Scale

as 4.5 or 5 (Table 9), causing higher solubility of aluminum, the hydrolyses of which produces this high exchangeable $[H^+]$. As Birrel (1964) pointed out, the base saturation values of some of these soils are low although the pH values are comparatively high. Swindale (1964) remarked that the values of the base saturation are highly unreliable since the base saturation determined in the laboratory at pH 7 may be much lower than the actual value in the field condition at a low pH. Lai's (1967) results of cation exchange capacity at different pH values support the above fact.

Particle Size Distribution

Results of the particle size distribution are shown in Tables 13 and 14. An examination of Table 13 indicates that the sum of the organic matter, free iron oxides, sand, silt, and clay adds up to <100 percent. Apart from the small loss during mechanical separation, the other reasons for this anomaly, in order of importance, are: (1) Loss of free alumina and silica when boiled with 2% Na_2CO_3 and during deferration process, (2) water of hydration associated with free iron oxides, and (3) standard conversion factor for the conversion of organic carbon to organic matter is low for these soils.

Textural class of these soils does not have the same significance as in other soils. Particle distribution analyses suffer from

Table 13. Mechanical Analyses of the Soils

Soil	Horizon	Sand >50μ	Silt 2-50μ	Total Clay <2μ	O.M.	Free Iron	Total	Loss
		%	%	%	%	%		
Apakuie	A1	21.22	29.09	13.96	28.45	7.44	100.16	+ 0.16
	B2	16.35	29.95	28.25	10.52	11.72	96.79	- 3.21
	IIAb	14.96	38.30	29.43	9.52	9.44	101.65	+ 1.65
	IIC1	43.45	17.01	13.53	5.69	8.44	88.12	-11.88
	IIC2	54.55	18.20	12.70	3.41	6.48	95.34	- 4.66
Hanaipoe	Ap1	4.71	19.50	11.34	36.74	9.92	82.21	-17.79
	Ap2	1.82	11.88	29.40	26.02	12.76	81.88	-18.12
	B21	1.81	15.96	31.20	20.02	12.76	80.75	-19.25
	B22	2.11	14.64	29.09	16.14	15.20	77.18	-22.82
	B23	2.39	21.31	43.55	15.02	11.78	97.03	- 2.97
	C	29.77	20.11	22.49	20.34	7.04	99.75	- 0.25
	B24b	3.61	25.04	37.84	10.67	12.72	89.88	-10.12
Umikoa	Ap	4.06	10.51	29.30	24.14	16.00	84.01	-15.99
	B21	2.12	7.27	27.85	19.45	12.72	69.41	-30.59
	C	2.77	7.96	52.60	16.74	10.08	90.15	- 9.85
	B22b	1.40	7.01	40.21	15.83	10.76	75.21	-24.79
	B23b	2.31	7.07	36.24	15.77	14.52	75.91	-24.09
	B24b	2.50	14.67	30.22	10.24	10.76	68.39	-31.61
Maile	A11, A12	9.85	10.05	24.6	19.05	30.36	93.91	- 6.09
	A13	2.12	8.58	35.2	19.84	11.60	77.34	-22.66
	IIB21, IIIB22, IVB23, VC	2.78	9.74	43.99	16.48	12.44	85.43	-14.57
	VIB24	1.35	7.84	25.72	15.52	14.72	65.15	-34.85
	VIIB25	3.73	11.87	51.39	15.86	9.20	92.05	- 7.95
	VIIIB26	6.26	34.3	41.41	9.79	8.00	99.76	- 0.24

Table 14. Percentages of Sand, Silt, Clay, and Textural Class

Soil	Horizon	Sand	Silt	Clay	Textural class	Field observation
Apakuie	A1	33.0	45.3	21.8	loam	loam
	B2	21.9	40.2	37.9	clay loam	very fine sandy loam
	Ab	16.2	46.7	37.1	silty clay loam	very fine sandy loam
	IIC1	58.7	22.9	18.4	sandy loam	very fine sandy loam
	IIC2	69.8	16.4	13.8	sandy loam	loamy sand
Hanaipoe	Ap1	13.2	54.9	31.9	silty clay loam	silt loam
	Ap2	4.2	27.6	68.2	clay	silt loam
	B21	3.7	32.7	63.9	clay	silt loam
	B22	4.6	31.9	63.5	clay	silt loam
	B23	3.6	31.6	64.8	clay	silt loam
	C	41.2	27.8	31.1	clay loam	compacted sand
	B24b	5.4	37.7	56.5	clay	silt loam
Umikoa	Ap	9.3	23.9	66.8	clay	silty clay loam
	B21	5.7	19.5	74.8	clay	silty clay loam
	C	4.3	12.6	83.1	clay	silty clay loam
	B22b	2.9	14.4	82.7	clay	silty clay loam
	B23b	5.1	15.5	79.4	clay	silty clay loam
	B24b	5.2	31.0	63.8	clay	silty clay loam
Maile	A11, A12	21.89	23.6	54.5	clay	silt loam
	A13	4.60	18.7	76.7	clay	silty clay loam
	IIB21, IIIB22, IVB23, VC	4.93	17.2	77.8	clay	silty clay loam
	VIB24	3.87	22.5	73.7	clay	silty clay loam
	VIIB25	5.57	17.7	76.7	clay	silty clay loam
	VIIIB26	7.3	42.0	50.7	silty clay	silty clay loam

nondispersibility of the clay. Percentages of sand, silt and clay are also calculated in terms of their total amount and presented in Table 14. Even with the poor dispersion, the texture of these soils, determined by means of laboratory analyses, is more clayey than the field observation.

Percentages of sand, silt and clay presented in Table 11 are not accurate since free iron oxides and free alumina and silica are not taken into account in the calculation of their percentages. Percent clay in these soils indicate their relative degree of weathering. Percent clay increases in the order: Apakuie < Hanaipoe < $\begin{matrix}\text{Umikoa} \\ \text{Maile}\end{matrix}$. This is to be expected from the amounts of median annual rainfall and soil temperatures of these soils. From Apakuie to Hanaipoe to Umikoa both rainfall and temperature increase, and, hence, the percent clay increases due to increasing degree of weathering. From Umikoa to Maile, the soil temperature is same, whereas the rainfall increases. The very slight decrease of clay from Umikoa to Maile is apparently not due to a decrease in the degree of weathering but due to decomposition of clay particles as indicated by Jenny (1941).

15-Bar Moisture Retention

High values were obtained for the 15-bar moisture as seen from Table 15. This is due to high amounts of amorphous colloids present in these soils.

Table 15. 15-Bar Moisture Retention of the Soils

Apakuie	
Horizons	15-bar moisture
A1	22.65
B2	26.95
IIAb	22.28
IIC1	23.31
IIC2	25.85
Mean*	23.75

Umikoa	
Horizons	15-bar moisture
Ap	61.69
B21	160.20
C	164.30
B22b	184.36
B23b	202.30
B24b	171.60
Mean*	156.22

Hanaipoe	
Horizons	15-bar moisture
Ap1	48.76
Ap2	91.49
B21	109.90
B22	113.30
B23	119.60
C	52.33
B24b	103.90
Mean*	98.38

Maile	
Horizons	15-bar moisture
A11, A12	40.51
A13	155.20
IIB21, IIIB22, IVB23, VIB24	164.00
VIB24	185.70
VIIB25	167.90
VIIIB26	114.30
Mean*	156.06

*Mean of all horizons except the last.

Fifteen-bar water increases from Apakuie to Hanaipoe and then to Maile and Umikoa in the sequence as seen in the Figure 14. Moisture retention depends on the amount of clay, type of clay and organic matter. In this sequence amount of clay increases in the order Apakuie < Hanaipoe < Umikoa and Maile (Table 14), whereas amount of amorphous material increases in the order Apakuie < Maile < Hanaipoe < Umikoa (Table 7). These two orders explain the variation of 15-bar moisture in this sequence of soils. It is also found that the surface horizons of Hanaipoe, Umikoa and Maile have lower 15-bar moisture than the subsoils. This may be due to the irreversible drying of the amorphous clay and due to the granular structure of the surface horizons.

DISCUSSION

Nature of Allophane

The term "allophane" cannot be precisely defined yet (Swindale, 1964) since different people have used the term in different ways. Originally allophane was defined as hydrous aluminosilicates which are amorphous to X-ray by Ross and Kerr (1934). They recommend that the term allophane should be restricted to mutual solid solution of silica, alumina, water and minor amounts of bases, but should include all such materials even though the proportion of these constituents may differ. There are other mineral colloids such as palagonite and the hydrous oxides of alumina, silica and iron which are also amorphous to X-ray. Fieldes (1955) considered allophane as the name given to all these amorphous colloidal minerals. He classified the allophane into allophane A, allophane B and allophane AB. Allophane A is the cross-linked type in which the silica and alumina are randomly combined. Allophane B is a discrete type of mixed silica plus alumina. It has been suggested that the term allophane should be confined to minerals with SiO_2/Al_2O_3 ratio between one and three (Swindale, 1964).

The different classes of allophane recognized by Fieldes (1955) can be distinguished by D.T.A., infra-red analyses and electron micrograph studies. Since the soils under discussion

were analyzed by D.T.A. only, the nature of their allophane shall be discussed in the light of the D.T.A. results. According to Fieldes (1955) the D.T.A. patterns of allophane A give only a single broad strong endothermic peak in the temperature region of 100 to 200°C and a sharp exothermic peak in the range 850°C to 1000°C. The presence of two endothermic peaks in the region 100 to 200°C are due to allophane B. The D.T.A. patterns of the fine clays and some of the coarse clays under the present study (Figures 8-9) resemble that of allophane A. The coarse clay fractions of some of the soils have D.T.A. patterns with the 900°C exothermic peak greatly reduced or absent. However, there are no two discrete endothermic peaks in the 150°C region. This indicates the possibility of the presence of allophane AB in the coarse clay fraction of some of the soils. Miyauchi and Aomine (1964) obtained similar results in some Japanese soils, and this caused them to question the presence of allophane B in their samples.

It is suggested that further investigations to characterize the nature of allophane in these soils be pursued employing infra-red studies.

Properties and Formation of Individual Soils

Apakuie Soil

Apakuie soil is probably developed from the ash deposits

from Puu Kihe cone. It is formed at high altitudes on Mauna Kea with median annual rainfall of 24 inches and soil temperature of 55°F.

The soil has large amounts of plagioclase feldspars, magnetite, and volcanic glass together with small amounts of olivine and pyroxenes in the sand and silt fractions. The clay fraction consists mainly of allophane. This soil has the highest amount of allophane in the clay fraction indicating that the allophane formed is not decomposed to other minerals. All these facts indicate that the soil is not highly weathered due to the mild climate of this area.

An abrupt wavy boundary between the B2 and IIAb horizon indicates that there is a lithologic discontinuity at this level. The variation of pH, organic carbon, cation exchange capacity, and exchangeable Ca down the profile indicate that either the soil is formed on one ash deposit without any buried horizons or sufficient time has not been available for the buried horizons to develop, if there are any.

As seen from the particle size distribution, this soil is slightly medium to coarse in texture, mainly in the last two horizons. The cation exchange capacity and 15-bar water are not so low as expected from the relatively small amount of clay, because the clay contains allophane. Cation exchange capacity is found to decrease with depth due to decrease in the amount of clay. Base

Table 16. Summary of the Properties of Apakuie

Properties	A1	B2	IIAb	IIC1	IIC2
Primary minerals	P.F., V.G., Mg, Ol	P.F., V.G., Mg, Ol	P.F., V.G., Mg, Ol	P.F., V.G., Mg, Ol	P.F., V.G., Mg, Ol
Secondary minerals	All	All	All	All	All
pH_{H_2O}	5.82	6.45	6.70	6.82	6.95
ΔpH	0.42	0.95	1.05	1.04	1.20
C	16.50	6.10	5.52	3.30	1.98
N	1.102	0.580	0.432	0.238	0.134
C/N	14.97	10.52	12.78	13.86	14.78
C.E.C.	40.8	41.9	38.5	29.6	15.0
Ca	19.40	10.85	10.70	8.53	3.81
Mg	3.52	1.60	1.40	1.35	0.62
K	0.92	0.58	0.42	0.45	0.62
Na	0.061	0.074	0.060	0.070	0.072
B.S.	58.58	31.26	32.68	35.14	34.13
Free Iron Oxides in 100 gm mineral soil	10.40	13.10	10.43	8.95	6.71
Percent Soil	33.0	21.9	16.2	58.7	69.8
Percent Silt	45.3	40.2	46.7	22.9	16.4
Percent Clay	21.8	37.9	37.1	18.4	13.8
15-bar water	22.65	26.95	22.28	23.31	25.85

P.F.: Plagioclase Feldspars
V.G.: Volcanic Glass
Mg : Magnetite
All : Allophane
Ol : Olivine

saturation is high with values ranging from 32 to 58 percent. The high amounts of exchangeable Ca are probably due to the presence of high amounts of plagioclase feldspar which continue to weather. The low amount of rain in this area did not leach all the bases.

The organic matter is very high in the A1 horizon and decreases down the profile. The pH values indicate a slightly acid to neutral reaction in these soils. The increase of pH down the profile may be due to the decrease of organic matter down the profile. The decrease of free iron oxides down the profile is expected from the decrease of acidity and degree of weathering.

Hanaipoe Soil

The nature of the parent material from which the Hanaipoe soil is derived is not known. According to the map described by Macdonald and Stearns (1946), the location of the Hanaipoe shows that it is formed on lava flows. However, the morphology of the soil and the high amount of allophane detected indicates that it is derived from volcanic ash probably of the same origin as Apakuie.

The mineralogy of this soil is similar to Apakuie. Dominant minerals present in the sand and silt fractions are plagioclase feldspar, volcanic glass, magnetite and small amounts of olivine and pyroxenes. The clay fraction is composed mainly of allophane.

Particle size distributions indicate that there are one or more buried horizons present. There is a definite, sharp change in the amount of sand in the C horizon. This may be due to a difference in the physical nature of the ash from which this horizon is derived; it was probably denser, coarser and more compact, and, therefore, more resistant to weathering than the later deposits. Because the weathering in the C horizon is low, the amounts of free iron, cation exchange capacity, and 15-bar water are also low. C/N ratio of this horizon is high compared to those of the adjacent horizons. This may be due to the high pH and the compacted sandy nature which produce anaerobic conditions for the decomposition of organic carbon. The high amount of sand and low amount of clay in the Ap1 horizon may be due to irreversible drying of the allophanic clay. This is probably the reason for the low cation exchange capacity and 15-bar water of this horizon, compared to the other horizons.

The pH values indicate that the soil is slightly acid in reaction. The organic carbon is found to decrease downwards in the profile. The highest amount of organic carbon in the whole sequence is found in the Ap1 horizon of Hanaipoe. The low pH of this horizon may be due to this high amount of organic carbon.

Base saturation is found to decrease down the profile with a fairly abrupt change between the B21 and B22 horizons, showing that in ash-derived soils the weathering is high in the bottom and

Table 17. Summary of the Properties of Hanaipoe

Properties	Ap1	Ap2	B21	B22	B23	C	B24b
Primary minerals	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol	P.F., Mg, V.G., Ol
Secondary minerals	All	All	All	All	All	All	All
pH_{H_2O}	5.10	6.00	6.20	5.95	6.00	6.45	6.18
ΔpH	0.50	0.75	0.99	0.97	0.95	1.07	0.98
C	21.31	15.09	11.61	9.36	8.71	4.64	6.19
N	1.579	1.039	0.730	0.666	0.594	0.241	0.489
C/N	13.50	14.52	15.90	14.05	14.66	19.25	12.66
C.E.C.	56.5	85.9	85.8	88.0	81.4	52.6	81.8
Ca	10.4	20.0	13.6	5.37	2.77	1.21	2.03
Mg	7.3	4.53	4.13	1.81	1.81	0.77	0.18
K	0.46	0.25	0.20	0.01	0.09	0.09	0.03
Na	0.059	0.077	0.219	0.191	0.182	0.062	0.128
B.S.	32.19	28.94	21.15	8.39	5.96	4.05	2.90
Free Iron Oxides in 100 mg of mineral soil	15.68	17.25	15.95	18.13	13.84	7.65	14.24
Percent Sand	13.2	4.2	3.7	4.6	3.6	41.2	5.4
Percent Silt	54.9	27.6	32.7	31.9	31.6	27.8	37.7
Percent Clay	31.9	68.2	63.9	63.5	64.8	31.1	56.5
15-Bar Water	48.76	91.49	109.9	113.3	119.6	52.33	103.9

P.F.: Plagioclase Feldspar Ol: Olivine
Mg : Magnetite All: Allophane
V.G.: Volcanic Glass

low in the top and therefore, the process of releasing and leaching of bases is higher in the bottom than in the top.

Profile development in this soil is confined only to the formation of a granular epipedon. This epipedon is dark and has high amounts of organic carbon and low amounts of base saturation (<50%); it meets the criteria for an Umbric epipedon.

Umikoa Soil

Umikoa is probably developed on volcanic ash deposited from the summit cones of Mauna Kea (Frazer, 1960). This soil has a median annual rainfall of 55" and a mean soil temperature of 65°F.

Dominant minerals in the sand and silt fractions are magnetite, quartz and small amounts of plagioclase feldspars, olivine and ilmenite. The clay fractions contain allophane and gibbsite as major constituents with very small amounts of layer silicates. Quartz is found to decrease from the surface down to the C horizon and then increases to the next horizon and then decreases again. The pH is found to increase down to the C horizon and then decreases gradually downwards. Mineralogical analyses show that C horizon is highly amorphous and has the least amount of layer silicates when compared to the other horizons of this soil. All of these findings tend to indicate that less soil formation has taken place in the C horizon than in the other horizons of the profile. This anomaly is probably due to the formation of surface horizons formed on parent material deposited on well developed horizons buried below the C.

Table 18. Summary of the Properties of Umikoa

Properties	Ap	B21	C	B22b	B23b	B24b
Primary minerals	P.F., Mg Ol	P.F., Mg Ol, Il	P.F., Mg Ol, Il	P.F., Mg Ol, Il	P.F., Mg Ol, Il	P.F., Mg Ol, Il
Secondary minerals	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr
pH_{H_2O}	5.85	5.95	5.98	5.90	5.80	5.65
ΔpH	1.02	0.90	0.85	0.80	0.68	0.50
C	14.00	11.28	9.71	9.18	9.15	5.94
N	1.062	0.623	0.539	0.466	0.545	0.445
C/N	13.18	18.11	18.01	19.70	16.79	13.35
Free Iron Oxides in 100 gm. mineral soil	21.09	15.79	12.11	12.78	17.24	11.99
C.E.C.	72.1	94.9	94.7	93.0	97.0	79.1
B.S.	12.02	9.93	6.49	3.86	3.08	3.11
Ca	6.21	7.54	4.96	3.11	2.00	1.23
Mg	2.0	1.6	1.05	0.28	0.50	0.95
K	0.37	0.14	0.11	0.09	0.17	0.16
Na	0.091	0.142	0.036	0.114	0.315	0.115
Percent Sand	9.3	5.7	4.3	2.9	5.1	5.2
Percent Silt	23.9	19.5	12.6	14.4	15.5	31.0
Percent Clay	66.8	74.8	83.1	82.7	79.4	63.8
15-Bar Water	61.69	160.2	164.2	184.6	202.3	171.6

P.F.: Plagioclase Feldspar
Mg : Magnetite
Ol : Olivine
Qr: Quartz
Gb: Gibbsite
Kl : Kaolin
Vr.: Vermiculite
Mc : Mica
Il : Ilmenite

Comparatively higher base saturation of the first three surface horizons further supports the above view.

The pH values indicate a slightly acid reaction in the soil and show insignificant differences within the profile. Except for the Ap horizon, all of the other horizons have similar cation exchange capacity, water held at 15-bar tension, organic carbon and pH_{H_2O} showing that the soil materials within the profile are uniformly redistributed by the soil forming processes or weathering has brought the different materials to the same equilibrium end point.

The Ap horizon has different properties from the lower horizons probably because of irreversible drying of allophanic clay. It has a low cation exchange capacity, percent clay, and low 15-bar water. Organic carbon and base saturation are found to decrease uniformly down the profile. The decrease of base saturation is due to the same reason as Hanaipoe.

Maile Soil

Maile soil occurs at the lowest elevation in the sequence. It has a median annual rainfall of 72" and a mean soil temperature of 65°F. For the sequence under study, this soil shows the highest degree of weathering.

Main minerals present in the sand and silt fractions are magnetite and very little ilmenite, olivine and volcanic glass. The clay fraction contains quartz, gibbsite, kaolin, mica and vermiculite.

The near absence of volcanic glass and feldspars show that this soil is highly weathered. The small amount of allophane in the clay fraction of this soil compared to the other soils in the sequence indicates that some of the allophane has been converted to layer silicates or gibbsite. Quartz is found to be high, as expected from the rainfall of this soil. The quartz decreases from the surface to the third horizon (IIB21, IIIB22, IVB23, VC) and then increases immediately to VIB24, and finally decreases again in the horizons below. This indicates the presence of at least one buried horizon. The profile description shows the presence of many buried horizons. Variations in the amounts of total exchangeable cations and percent base saturation with depth follows a zig-zag pattern supporting the presence of buried horizons. It is worthy to note that the other properties like pH, percent organic carbon, percent free iron oxides, percent clay, percent water held at 15-bar pressure exhibit remarkably uniform values in all horizons. This indicates that, although lithologic discontinuities exist in this profile, the soil forming processes have redistributed the soil materials within the profile or brought the different materials to virtually the same equilibrium end point.

The surface horizon (A11, A12) shows extremely different properties from the other horizons. Percent base saturation, percent sand, percent free iron oxides in the surface horizon are very high compared to the lower horizons. The pH and percent water

Table 19. Summary of the Properties of Maile

Properties	A11, A12	A13	IIB21, IIIB22, IVB23, VC	VIB24	VIIB25	VIIIB26
Primary minerals	Mg, Il, Ol	Mg, Il, Ol	Mg, Il, Ol	Mg, Il, Ol	Mg, Il, Ol	Mg, Il, Ol
Secondary minerals	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr	Qr, Gb, Kl Mc, Vr
pH_{H_2O}	4.68	5.32	5.50	5.55	5.50	5.92
ΔpH	0.30	0.39	0.23	0.23	0.37	0.42
C	11.05	11.51	9.56	9.00	9.20	5.08
N	0.636	0.685	0.560	0.440	0.428	0.208
C/N	17.37	16.80	17.07	20.45	21.50	24.42
Free Iron Oxides in 100 gm mineral soil	37.50	14.47	14.89	17.42	10.93	8.87
C.E.C.	37.1	66.6	40.9	53.6	75.4	37.5
B.S.	7.17	1.31	1.78	1.75	1.27	2.29
Ca	1.96	0.48	0.42	0.44	0.57	0.50
Mg	0.38	0.20	0.18	0.34	0.30	0.22
K	0.23	0.12	0.08	0.09	0.06	0.09
Na	0.091	0.073	0.048	0.066	0.029	0.051
Percent Sand	21.89	4.60	4.93	3.87	5.57	7.3
Percent Silt	23.6	18.7	17.2	22.5	17.7	42.0
Percent Clay	54.5	76.7	77.8	73.7	76.7	50.7
15-Bar Water	40.51	155.2	164.0	185.7	167.9	114.3

Mg: Magnetite
Il : Ilmenite
Ol : Olivine
Qr: Quartz
Gb: Gibbsite
Kl : Kaolin
Mc: Mica
Vr: Vermiculite

held at 15-bar tension are very much lower in the surface horizon than the other horizons. The apparent lower degree of weathering of the surface horizon which is exposed to high temperature and rainfall regime presents an interesting picture of the mutually opposing influences of various factors and processes of soil formation in an ash derived soil. The high temperature and high rainfall at the surface must have produced an alternate wet and dry condition which favors irreversible drying of the allophane clay. The irreversible drying of the clay has in all probability produced the higher amount of sand, lower 15-bar water and lower cation exchange capacity values. The granular structure, low moisture and alternate wet and dry conditions are probably the cause for the high free iron oxide content of this horizon. The low gibbsite content and high vermiculite content is expected from the low pH of this horizon.

The ΔpH values ($pH_{H_2O} - pH_{KCl}$) were found to be very low indicating that the net negative charge on the exchange complex is low. The reason for this low negative charge has been discussed in an earlier chapter of this thesis (Page 62).

Study of all these properties indicates that there is little profile development except for the darkening and formation of granular structure in the A horizon.

Genesis of the Sequence

The genesis of the soils in this sequence is considered on the assumption that all the soils are derived from volcanic ash under prevailing climatic conditions. Climate is the main factor which differentiates the soils. Although the present climatic condition do not necessarily represent the total environment throughout the formation of these soils, the relative values between the soil sites have remained essentially constant.

Main primary minerals found in the sand and silt fractions are volcanic glass, plagioclase feldspars, magnetite, quartz and small amounts of olivine and pyroxenes. Most workers have argued that quartz is formed as a secondary mineral in Hawaiian soils. The other primary minerals in the sand and silt fractions give an idea of the minerals present in the parent ash. The relative proportions of primary minerals present in the sand and silt fractions are not necessarily the same as the relative amounts of the minerals in the parent material, since minerals differ in their susceptibility to weathering.

The drastic decrease in the amount of feldspars in the silt fraction from Apakuie to Maile in the sequence indicates that the degree of weathering in the sequence increases from Apakuie to Maile as expected from the climate. It must be again noted that the mineral composition of the silt fraction depends to some extent on the mineral composition of the parent material, and, therefore,

the above statement is true only if the parent material of all these soils have similar mineral composition.

It is a general idea that allophane is the main constituent in all soils derived from volcanic ash. In the present study, the presence of allophane is detected from the background effects in X-ray diffraction patterns and from the first endothermic peak of the differential thermal analyses. Allophane in these soils must have been produced from the weathering of plagioclase feldspars and volcanic glass. Recently, Fieldes (1966) in his paper on the pedogenesis of allophane, mentioned that structural randomness in hydrous aluminum silicates is highly significant in the formation of allophane. According to him glass and feldspars which occur in volcanic ash soils have dis-ordered arrangement of silicon and aluminum, and, therefore, hydrous aluminum silicate clays formed from them are likely to have initially random structures corresponding to allophane.

According to Swindale and Sherman (1964), the formation of allophane in Hawaii is mainly due to the weathering of volcanic glass. They also mentioned that the volcanic glass weathers to yellow, brown and orange colored amorphous aluminosilicates called palagonite, in the initial stages, and this in turn produce allophane and then oxides with increasing degree of weathering. In the sequence under study, allophane in the clay fraction is found to decrease from Apakuie to Maile. This indicates that the

degree of weathering increases with increasing rainfall and temperature in the sequence, and, hence, the conversion of the allophane formed from the primary minerals to gibbsite or other minerals increases.

Amounts of free iron oxides increase from Apakuie to Maile in the sequence. Amounts of gibbsite are high in Maile and Umikoa and very low in Apakuie and Hanaipoe. This is to be expected from the climates of the soil sites. Under moderate or heavy rainfall, with both definite rainy and dry seasons, the soils would be enriched in iron oxides. Under continuous moist conditions with good internal drainage, aluminum oxide would become the most stable oxide in the weathering mass (Sherman, 1958). The subhorizons of Umikoa and Maile are considered to be continuously moist and hence gibbsite is abundant. In the surface horizons of Maile and Umikoa, a definite wet and dry condition exists due to the absorption of solar heat, and resulting in accumulation of large amounts of free iron oxides. Tamura (1952) studied similar soils formed under dry to very wet conditions in Hawaii and arrived at the same conclusion. The high amounts of allophane, gibbsite and free iron oxides are indicative of the advanced stage of weathering attained by these youthful andepts. This may be due to the high surface area of the volcanic ash parent material.

The stages of weathering of the volcanic glass and plagioclase feldspar in the formation of gibbsite have been discussed by many workers (Fieldes and Swindale, 1955; Kanno, 1962; Tamura and Jackson, 1953). In all these cases the parent material first produces an amorphous form of alumina or allophane and this in turn weathers to gibbsite by means of desilication.

The presence of small amounts of kaolin minerals in Umikoa and Maile indicates that they are either starting to form in the soil from allophane or if already formed in the soil are being decomposed. The presence of small amounts of kaolin minerals in Umikoa and Maile and its absence in the less weathered Apakuie and Hanaipoe tend to indicate that these minerals are in the early stages of formation rather than in the later stages of decomposition. Kaolin in the soil may have formed from allophane on completion of undirectional bonding through alternate wetting and drying in an acid media (Tamura and Jackson, 1953).

Small amounts of 2:1 minerals such as mica and vermiculite are also detected in Maile and Umikoa. These may be due to the resilication of gibbsite, allophane or kaolin. Vermiculite is found to occur in places of low base saturation and low pH. (Fieldes and Swindale, 1955). Maile and Umikoa provide similar conditions for the formation of this mineral. A 10 Å micaceous mineral is probably formed through the accumulation of K from the vegetation, in the interlayer positions of vermiculite.

$$\text{Mica} \underset{K^+}{\overset{H^+}{\rightleftharpoons}} \text{Vermiculite}$$

In higher rainfall areas, vegetation is abundant, and, hence, the release of K from the vegetation to soil is greater. In volcanic ash soils where the leaching is high because of high permiabilities, the relative amounts of vermiculite and mica depend on the relative intensities of leaching and K added from the vegetation.

The process of resilication to 2:1 minerals is due to silica being added from the vegetation or released from the relatively young ash deposits near the surface of the soils. Unlike other soils, from residuum these soils have the less weathered material found at the surface and more weathered material below.

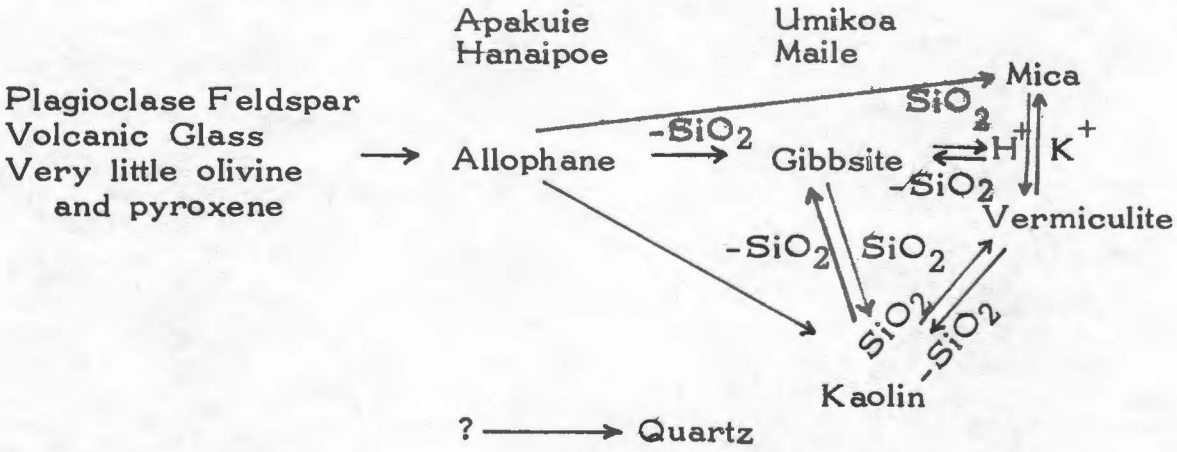
As mentioned in an earlier section, the formation of pedogenic quartz presents a problem in Hawaii. In the sequence under study, quartz increases with rainfall. It is also observed to be high in the surface horizons. There are essentially three theories presented for the formation of quartz in these soils:

1. Quartz from the North American continent is carried by the tradewinds and deposited with raindrops according to the rainfall sequence (Rex and Goldberg, 1958).
2. Quartz may be formed from the silica added from the vegetation. In the sequence under study, plant opal is identified mainly in the silt fractions of surface soils.

Quartz also is mainly found in the silt fractions of the surface horizons. Therefore, there may be a relation between the two.

3. Quartz may be formed by the devitrification of the glass present in these volcanic ash soils (Chichester, 1967). But this does not explain why quartz is found mainly in the surface horizons of high rainfall areas.

It is finally concluded that the main stages of weathering operating at the present stage of soil formation are:



The main processes which operates in the formation of these soils in order of occurrence are as follows:

1. Bases are released from the ash at the initial stages of weathering.
2. Subsequent leaching of bases and access of CO_2 would lower the pH and leads to precipitation of allophane from the silica and alumina released from the ash.

3. With further weathering allophane gives rise to kaolin minerals and gibbsite. Gibbsite is mainly formed by "desilication" of aluminosilicates in the form of allophane or kaolin. Free iron oxides are formed by a process of "laterization".
4. 2:1 layer silicates are formed by a process of "resilication" of allophane, kaolin or gibbsite.

Many trends of properties were found with climate. Regression lines were obtained for some of these properties. From the slope of these lines, values for the partial derivatives in Jenny's differential equation can be found. Substitution of these values, simplifies Jenny's equation, and, hence, makes the study of soil formation quantitative. This can be demonstrated by taking the soil property pH. Since pH mainly depends on rainfall and not on temperature,

$$\left(\frac{\partial pH}{\partial t}\right) \triangleq 0 \quad \text{and} \quad dpH = \left(\frac{\partial pH}{\partial r}\right) dr + \left(\frac{\partial pH}{\partial t}\right) dt$$

can be simplified as $dpH = \left(\frac{\partial pH}{\partial r}\right) dr$. Then the slope of the regression line of pH vs rainfall gives the value for the factor $\frac{\partial pH}{\partial r}$ i.e. $\frac{\partial pH}{\partial r} = -0.025$. In a similar manner, a value of -0.0186 for $\left(\frac{\partial(\Delta pH)}{\partial r}\right)$ was also obtained for another property ΔpH. The factor which is determined in this way simplifies Jenny's equation when applied to similar sequence with rainfall and other independent variables operating together on the soil

property. If a curvilinear regression is obtained for a soil property S, then the factor $\frac{\partial s}{\partial r}$ can be substituted by a function of r. In the sequence under discussion, a highly significant regression line of the form B.S. = 132.07 - 71.1 log r was obtained for B.S. vs rainfall (r).

$$\text{i.e.} \quad B.S. = 132.07 - \frac{71.1}{2.303} \ln r$$

$$\text{or} \quad \left(\frac{\partial (B.S.)}{\partial r}\right) = - \frac{71.1}{2.303} r$$

Classification of the Soils

The latest Soil Conservation Service classification of the soils under discussion was examined in the light of the results of all the analyses done and the morphology of the soils. Differential thermal analyses showed that these soils have high amount of amorphous colloids in their clay fraction. Examination under the petrographic microscope revealed the presence of pyroclastic materials in the sand and silt fractions. These soils have dark-colored surface horizons containing high amount of organic carbon and having base saturation less than 50 percent (NH_4OAc; pH 7). These horizons fit the descriptions of the Umbric epipedon. The soils lack the characteristics associated with wetness defined for aquepts. These properties prove that the soils should be classified in the suborder andepts.

The soils have mean annual soil temperature greater than

47°F, and, hence, do not belong to the group cryandepts. The absence of duripans and mollic epipedon indicate that none of them belong to the groups durandepts or eutrandepts. The clays of all these soils have the properties of irreversible drying, but not into gravel sized aggregates, and, hence, they do not belong to the group hydrandepts.

The following groups and subgroups are defined according to the latest unpublished Soil Conservation Service classification (1966, Oct.).

Dystrandepts are other andepts which have an umbric or ochric epipedon and textures of fine-loamy, fine-silty or finer and 15-bar water greater than 20 percent.

Typic Dystrandepts are dystrandepts that:

a. Lack mottles with chromas of 2 or less within 40" of the surface.

b. Have an umbric epipedon 10" or more thick.

c. Are dry in some horizons between 10" to 40" at some time in most years.

d. Lack a lithic contact within 20" of the surface.

e. Have cation exchange capacity of more than 30 m.e./100 gm of soil (by NH_4OAc) in all horizons.

Hydric Dystrandepts are like typic dystrandepts except for c.

The property (c) depends on the rainfall of the area where the soil is formed. Soil found under a mean annual rainfall of

above 70 inches can be considered as always wet. Soil found under mean annual rainfall below 40" or 50" can be considered to have the property (c).

Hanaipoe and Maile have all the properties of Typic dystrandepts and Hydric dystrandepts, respectively. Umikoa is found under a mean annual rainfall of 55 inches which is perhaps slightly too high for the soils to have the property (c) of typic dystrandept. Without field evidence of dryness it cannot be classified definitely either as typic dystrandepts or hydric dystrandepts. This is to be expected since Umikoa is formed between Maile (hydric dystrandepts) and Hanaipoe (typic dystrandept).

Apakuie is classified as an umbric Vitrandept by the Soil Conservation Service in their profile description. Vitrandepts have textures of coarse silty, coarse loamy or coarser based on the whole soil or the 15-bar water retention is 20 percent or less. Apakuie is found to have an umbric epipedon, mean 15-bar moisture of 24 percent and fine loamy to fine silty texture. These properties indicate that Apakuie belongs to the dystrandepts and not to vitrandepts. Apakuie also has all the properties of typic dystrandepts except the umbric epipedon is less than 10 inches thickness. Therefore, it is suggested that it should be classified as an entic dystrandept.

The changes in the classification during the last few years are given in the following table.

Soils	Cline 1955	S.C.S.* 1965	S.C.S.* (Oct., 1965)	Suggested Improvements
Apakuie	Latosolic Brown Forest	Eutric Vitrandepts	Umbric Vitrandepts	Entic Dystrandepts
Hanaipoe	Latosolic Brown Forest	Typic Normandepts	Typic Dystrandepts	Typic Dystrandepts
Umikoa	Latosolic Brown Forest	Typic Normandepts	Typic Dystrandepts	Typic Dystrandepts
Maile	Latosolic Brown Forest	Hydric Normandepts	Hydric Dystrandepts	Hydric Dystrandepts

*Soil Conservation Service

SUMMARY AND CONCLUSIONS

1. Four soils classified as dystrandepts taken from the middle elevations of Mauna Kea, Hawaii, showed variations in properties that were closely correlated with variations in rainfall.

2. The soils contained plagioclase feldspars in the silt and sand fractions of some horizons together with magnetite, plant opal and small amounts of olivine and pyroxenes.

3. The clay fraction of all soils contained allophane. Umikoa and Maile, the two wetter members, contain gibbsite and a little kaolin, mica and vermiculite. The amount of allophane in the clay fraction was found to decrease in the order: Apakuie > Hanaipoe > Umikoa > Maile; whereas the amount of allophane in the whole soil was found to increase in the order: Apakuie < Maile < Hanaipoe < Umikoa.

4. Soil pH was neutral to slightly acid. The decrease of pH in the sequence was highly correlated with increase of rainfall. The pH was always found to be lower in the surface horizon than the horizons below.

5. Percentage carbon and nitrogen were found to be very high and highly correlated with each other. The variation in carbon and nitrogen content in the sequence indicated that they are dependent on both temperature and rainfall.

6. Free iron oxides in the mineral soils ranged from 6.7 to 37.5 percent, with greatest amounts in the surface horizon of Maile. In the sequence, it increased with increasing temperature and rainfall.

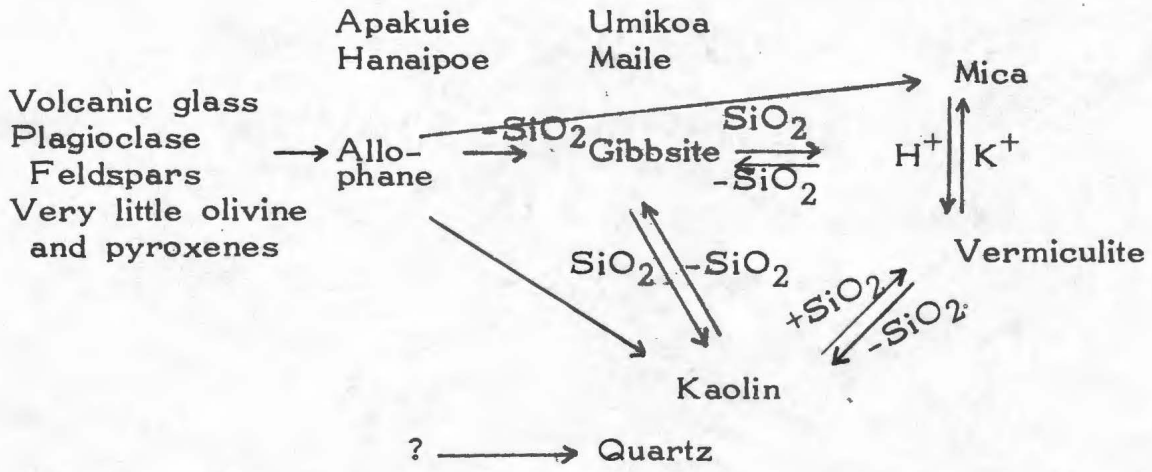
7. The high cation exchange capacities and 15-bar water contents of these soils were correlated with the high amounts of allophane.

8. Base saturation varied logarithmically with the rainfall as expected from fundamental principles of thermodynamics. The relative abundance of the exchangeable bases decreased in the order: Ca > Mg > K > Na.

9. The texture of these soils was found to be clayey except Apakuie which was slightly coarser than the rest. This indicates that the soils are moderate to highly weathered with the degree of weathering increasing in the order: Apakuie < Hanaipoe < Umikoa < Maile. Laboratory analyses show more clayey texture than field observations.

10. The allophane in these soils is mainly allophane A, in which the silica and alumina are randomly combined.

11. The stage of mineral transformation with soil formation at the present time, in the four soils, is summarized as follows:



12. Quartz was found to increase with increasing rainfall in the sequence with high amounts in the silt fraction of surface horizons.

13. Profile differentiation was confined to the formation of dark, granular epipedons, except in the Maile soil where additional differences occurred in the surface horizon.

14. Numerical values for the factor $\frac{\partial S}{\partial r}$ of Jenny's soil formation equation were obtained. The soil properties (S) studied were base saturation, pH and ΔpH.

15. Apakuie is moderately weathered, neutral to slightly acid, with moderate amount of base saturation and medium cation exchange capacity.

16. Hanaipoe is moderate to strongly weathered, slightly acid in reaction, with low base saturation, high cation exchange capacity and very high organic matter.

17. Umikoa is highly weathered, slightly acid in reaction, with very low base saturation, high cation exchange capacity and high organic matter.

18. Maile is very highly weathered, acid in reaction, with very low base saturation, high cation exchange capacity and high organic matter.

19. Apakuie, the driest and least weathered is classified as an entic dystrandept; Hanaipoe and Umikoa as typic dystrandepts, and Maile the wettest and most weathered as a hydric dystrandept.

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